Virtual Reality – History, Applications, Technology and Future

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Virtual Reality
History, Applications, Technology and Future

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Abstract

Virtual Reality (VR), sometimes called Virtual Environments (VE) has drawn much attention in the last few years. Extensive media coverage causes this interest to grow rapidly. Very few people, however, really know what VR is, what its basic principles and its open problems are.

In this paper a historical overview of virtual reality is presented, basic terminology and classes of VR systems are listed, followed by applications of this technology in science, work, and entertainment areas. An insightful study of typical VR systems is done. All components of VR application and interrelations between them are thoroughly examined: input devices, output devices and software. Additionally human factors and their implication on the design issues of VE are discussed. Finally, the future of VR is considered in two aspects: technological and social. New research directions, technological frontiers and potential applications are pointed out. The possible positive and negative influence of VR on life of average people is speculated.

1.   Introduction

1.1.   History

Nowadays computer graphics is used in many domains of our life. At the end of the 20th century it is difficult to imagine an architect, engineer, or interior designer working without a graphics workstation. In the last years the stormy development of microprocessor technology brings faster and faster computers to the market. These machines are equipped with better and faster graphics boards and their prices fall down rapidly. It becomes possible even for an average user, to move into the world of computer graphics. This fascination with a new (ir)reality often starts with computer games and lasts forever. It allows to see the surrounding world in other dimension and to experience things that are not accessible in real life or even not yet created. Moreover, the world of three-dimensional graphics has neither borders nor constraints and can be created and manipulated by ourselves as we wish – we can enhance it by a fourth dimension: the dimension of our imagination...

But not enough: people always want more. They want to step into this world and interact with it – instead of just watching a picture on the monitor. This technology which becomes overwhelmingly popular and fashionable in current decade is called *Virtual Reality* (VR). The very first idea of it was presented by Ivan Sutherland in 1965: "make that (virtual) world in the window look real, sound real, feel real, and respond realistically to the viewer's actions" [Suth65]. It has been a long time since then, a lot of research has been done and status quo: "the Sutherland's challenge of the Promised Land has not been reached yet but we are at least in sight of it" [Broo95].

Let us have a short glimpse at the last three decades of research in virtual reality and its highlights [Bala93a, Cruz93a, Giga93a, Holl95]:

- **Sensorama** – in years 1960-1962 Morton Heilig created a multi-sensory simulator. A prerecorded film in color and stereo, was augmented by binaural sound, scent, wind and vibration experiences. This was the first approach to create a virtual reality system and it had all the features of such an environment, but it was not interactive.

- **The Ultimate Display** – in 1965 Ivan Sutherland proposed the ultimate solution of virtual reality: an artificial world construction concept that included interactive graphics, force-feedback, sound, smell and taste.

- **"The Sword of Damocles"** – the first virtual reality system realized in hardware, not in concept. Ivan Sutherland constructs a device considered as the first *Head Mounted Display* (HMD), with appropriate head tracking. It supported a stereo view that was updated correctly according to the user's head position and orientation.

- **GROPE** – the first prototype of a force-feedback system realized at the University of North Carolina (UNC) in 1971.

- **VIDEOPLACE** – Artificial Reality created in 1975 by Myron Krueger – "a conceptual environment, with no existence". In this system the silhouettes of the users grabbed by the cameras were projected on a large screen. The participants were able to interact one with the other thanks to the image processing techniques that determined their positions in 2D screen's space.

- **VCASS** – Thomas Furness at the US Air Force's Armstrong Medical Research Laboratories developed in 1982 the Visually Coupled Airborne Systems Simulator – an advanced flight simulator. The fighter pilot wore a HMD that augmented the out-the-window view by the graphics describing targeting or optimal flight path information.

- **VIVED** – VIrtual Visual Environment Display – constructed at the NASA Ames in 1984 with off-the-shelf technology a stereoscopic monochrome HMD.

- **VPL** – the VPL company manufactures the popular DataGlove (1985) and the Eyephone HMD (1988) – the first commercially available VR devices.

- **BOOM** – commercialized in 1989 by the Fake Space Labs. BOOM is a small box containing two CRT monitors that can be viewed through the eye holes. The user can grab the box, keep it by the eyes and move through the virtual world, as the mechanical arm measures the position and orientation of the box.

- **UNC Walkthrough project** – in the second half of 1980s at the University of North Carolina an architectural walkthrough application was developed. Several VR devices were constructed to improve the quality of this system like: HMDs, optical trackers and the Pixel-Plane graphics engine.

- **Virtual Wind Tunnel** – developed in early 1990s at the NASA Ames application that allowed the observation and investigation of flow-fields with the help of BOOM and DataGlove (see also section 1.3.2).

- **CAVE** – presented in 1992 CAVE (CAVE Automatic Virtual Environment) is a virtual reality and scientific visualization system. Instead of using a HMD it projects stereoscopic images on the walls of room (user must wear LCD shutter glasses). This approach assures superior quality and resolution of viewed images, and wider field of view in comparison to HMD based systems (see also section 2.5.1).

- **Augmented Reality (AR)** – a technology that "presents a virtual world that enriches, rather than replaces the real world" [Brys92c]. This is achieved by means of see-through HMD that superimposes virtual three-dimensional objects on real ones. This technology was previously used to enrich fighter pilot's view with additional flight information (VCASS). Thanks to its great potential – the enhancement of human vision – augmented reality became a focus of many research projects in early 1990s (see also section 1.3.2).

1.2.   What is VR? What is VR not?

At the beginning of 1990s the development in the field of virtual reality became much more stormy and the term Virtual Reality itself became extremely popular. We can hear about Virtual Reality nearly in all sort of media, people use this term very often and they misuse it in many cases too. The reason is that this new, promising and fascinating technology captures greater interest of people than e.g., computer graphics. The consequence of this state is that nowadays the border between 3D computer graphics and Virtual Reality becomes fuzzy. Therefore in the following sections some definitions of Virtual Reality and its basic principles are presented.

1.2.1.   Some basic definitions and terminology

Virtual Reality (VR) and *Virtual Environments* (VE) are used in computer community interchangeably. These terms are the most popular and most often used, but there are many other. Just to mention a few most important ones: *Synthetic Experience*, *Virtual Worlds*, *Artificial Worlds* or *Artificial Reality*. All these names mean the same:

- "Real-time interactive graphics with three-dimensional models, combined with a display technology that gives the user the immersion in the model world and direct manipulation." [Fuch92]

- "The illusion of participation in a synthetic environment rather than external observation of such an environment. VR relies on a three-dimensional, stereoscopic head-tracker displays, hand/body tracking and binaural sound. VR is an immersive, multi-sensory experience." [Giga93a]

- "Computer simulations that use 3D graphics and devices such as the DataGlove to allow the user to interact with the simulation." [Jarg95]

- "Virtual reality refers to immersive, interactive, multi-sensory, viewer-centered, three-dimensional computer generated environments and the combination of technologies required to build these environments." [Cruz93a]

- "Virtual reality lets you navigate and view a world of three dimensions in real time, with six degrees of freedom. (...) In essence, virtual reality is clone of physical reality." [Schw95]

Although there are some differences between these definitions, they are essentially equivalent. They all mean that VR is an interactive and immersive (with the feeling of presence) experience in a simulated (autonomous) world [Zelt92] (see fig. 1.2.1.1) – and this measure we will use to determine the level of advance of VR systems.
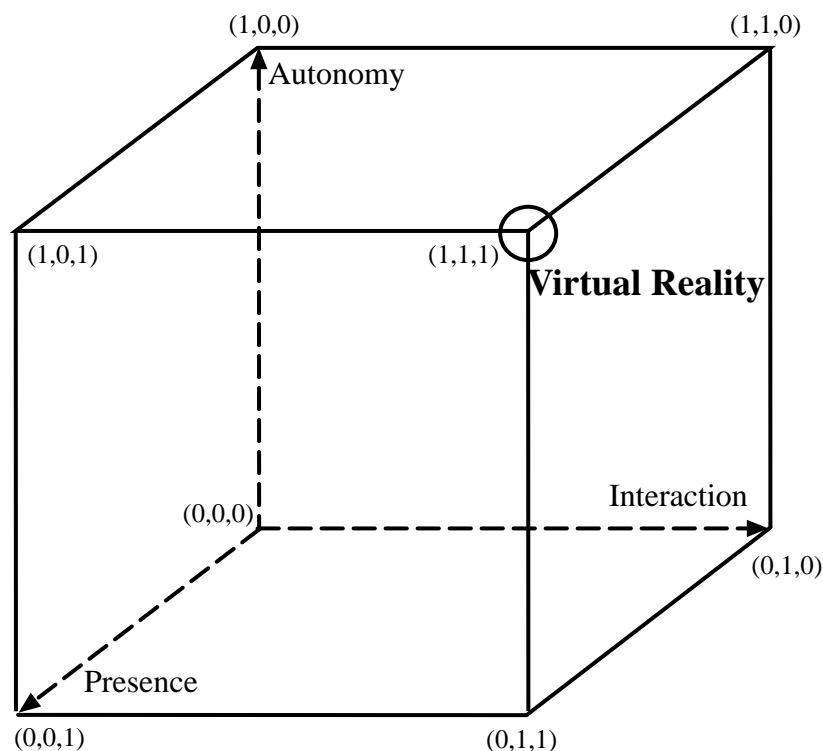

Figure 1.2.1.1. Autonomy, interaction, presence in VR – Zeltzer's cube (adapted from [Zelt92]).

Many people, mainly the researchers use the term Virtual Environments instead of Virtual Reality "because of the hype and the associated unrealistic expectations" [Giga93a]. Moreover, there are two important terms that must be mentioned when talking about VR: *Telepresence* and *Cyberspace*. They are both tightly coupled with VR, but have a slightly different context:

- **Telepresence** – is a specific kind of virtual reality that simulates a real but remote (in terms of distance or scale) environment. Another more precise definition says that telepresence occurs when "at the work site, the manipulators have the dexterity to allow the operator to perform normal human functions; at the control station, the operator receives sufficient quantity and quality of sensory feedback to provide a feeling of actual presence at the worksite" [Held92].

- **Cyberspace** – was invented and defined by William Gibson as "a consensual hallucination experienced daily by billions of legitimate operators (...) a graphics representation of data abstracted from the banks of every computer in human system" [Gibs83]. Today the term Cyberspace is rather associated with entertainment systems and World Wide Web (Internet).

1.2.2. Levels of immersion in VR systems

In a virtual environment system a computer generates sensory impressions that are delivered to the human senses. The type and the quality of these impressions determine the level of immersion and the feeling of presence in VR. Ideally the high-resolution, high-quality and consistent over all the displays, information should be presented to all of the user's senses [Slat94]. Moreover, the environment itself should react realistically to the user's actions. The practice, however, is very different from this ideal case. Many applications stimulate only one or a few of the senses, very often with low-quality and unsynchronized information. We can group the VR systems accordingly to the level of immersion they offer to the user (compare with [Isda93, Schw95]):

- **Desktop VR** – sometimes called Window on World (WoW) systems. This is the simplest type of virtual reality applications. It uses a conventional monitor to display the image (generally monoscopic) of the world. No other sensory output is supported.

- **Fish Tank VR** – improved version of Desktop VR. These systems support head tracking and therefore improve the feeling of "of being there" thanks to the motion parallax effect. They still use a conventional monitor (very often with LCD shutter glasses for stereoscopic viewing) but generally do not support sensory output.

- **Immersive systems** – the ultimate version of VR systems. They let the user totally immerse in computer generated world with the help of HMD that supports a stereoscopic view of the scene accordingly to the user's position and orientation. These systems may be enhanced by audio, haptic and sensory interfaces.

1.3.   Applications of VR

1.3.1.   Motivation to use VR

Undoubtedly VR has attracted a lot of interest of people in last few years. Being a new paradigm of user interface it offers great benefits in many application areas. It provides an easy, powerful, intuitive way of human-computer interaction. The user can watch and manipulate the simulated environment in the same way we act in the real world, without any need to learn how the complicated (and often clumsy) user interface works. Therefore many applications like flight simulators, architectural walkthrough or data visualization systems were developed relatively fast. Later on, VR has was applied as a teleoperating and collaborative medium, and of course in the entertainment area.

1.3.2.   Data and architectural visualization

For a long time people have been gathering a great amount of various data. The management of megabytes or even gigabytes of information is no easy task. In order to make the full use of it, special visualization techniques were developed. Their goal is to make the data perceptible and easily accessible for humans. Desktop computers equipped with visualization packages and simple interface devices are far from being an optimal solution for data presentation and manipulation. Virtual reality promises a more intuitive way of interaction.

The first attempts to apply VR as a visualization tool were architectural walkthrough systems. The pioneering works in this field were done at the University of North Carolina beginning after year 1986 [Broo86], with the new system generations developed constantly [Broo92b]. Many other research groups created impressive applications as well – just to mention the visualization of St. Peter Basilica at the Vatican presented at the Virtual Reality World'95 congress in Stuttgart or commercial Virtual Kitchen design tool. What is so fantastic about VR to make it superior to a standard computer graphics? The feeling of presence and the sense of space in a virtual building, which cannot be reached even by the most realistic still pictures or animations. One can watch it and perceive it under different lighting conditions just like real facilities. One can even walk through non-existent houses – the destroyed ones (see fig. 1.3.2.1) like e.g., the Frauenkirche in Dresden, or ones not even created yet.

Another discipline where VR is also very useful is scientific visualization. The navigation through the huge amount of data visualized in three-dimensional space is almost as easy as walking. An impressive example of such an application is the Virtual Wind Tunnel [Brys93f, Brys93g] developed at the NASA Ames Research Center. Using this program the scientists have the possibility to use a data glove to input and manipulate the streams of virtual smoke in the airflow around a digital model of an airplane or space-shuttle. Moving around (using a BOOM display technology) they can watch and analyze the dynamic behavior of airflow and

easily find the areas of instability (see fig. 1.3.2.2). The advantages of such a visualization system are convincing – it is clear that using this technology, the design process of complicated shapes of e.g., an aircraft, does not require the building of expensive wooden models any more. It makes the design phase much shorter and cheaper. The success of NASA Ames encouraged the other companies to build similar installations – at Eurographics'95 Volkswagen in cooperation with the German Fraunhofer Institute presented a prototype of a virtual wind tunnel for exploration of airflow around car bodies.
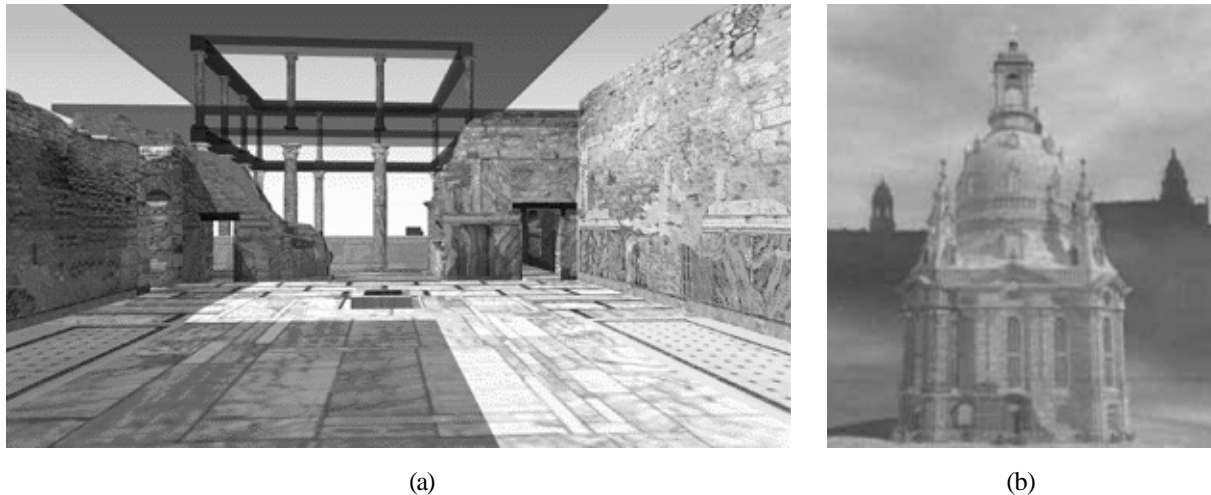

(a)   (b)

Figure 1.3.2.1. VR in architecture: (a) Ephesos ruins (TU Vienna), (b) reconstruction of destroyed Frauenkirche in Dresden (IBM).

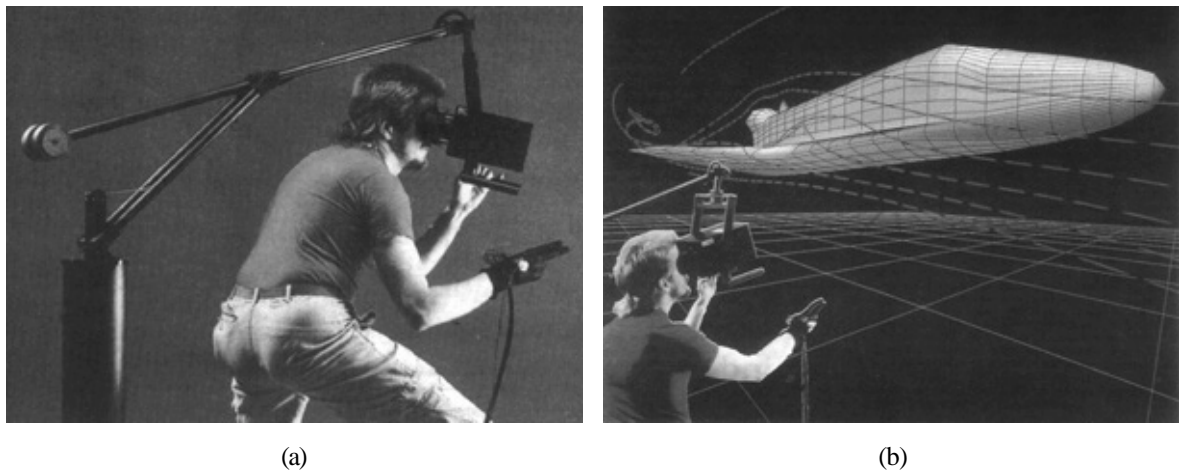(a)   (b)

Figure 1.3.2.2. Exploration of airflow using Virtual Wind Tunnel developed at NASA Ames: (a) outside view, (b) inside view (from [Brys93f]).

Other disciplines of scientific visualization that have also profited of virtual reality include visualization of chemical molecules (see fig. 1.3.2.3), the digital terrain data of Mars surface [Hitc93] etc.

Figure 1.3.2.3. VR in chemistry: exploration of molecules.

Augmented reality (see fig. 1.3.2.4) offers the enhancement of human perception and was applied as a virtual user's guide to help completing some tasks: from the easy ones like laser printer maintenance [Brys92c] to really complex ones like a technician guide in building a wiring harness that forms part of an airplane's electrical system [Caud92]. An other example of augmented reality application was developed at the UNC: its goal was to enhance a doctor's view with ultrasonic vision to enable him/her to gaze directly into the patient's body [Baju92].
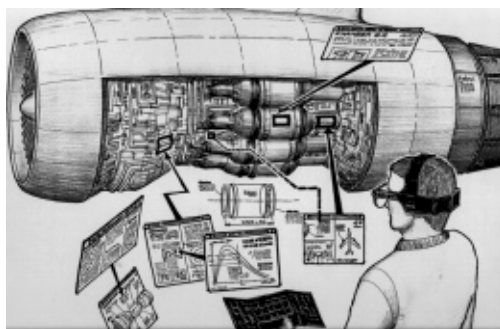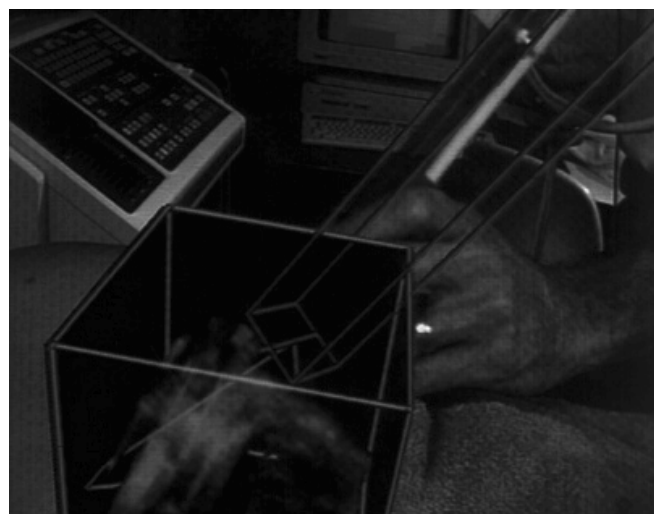
(a)   (b)

Figure 1.3.2.4. Augmented Reality: (a) idea of AR (UNC),

(b) augmented reality ultrasound system (from [Stat95]).

1.3.3. Modeling, designing and planning

In modeling virtual reality offers the possibility of watching in real-time and in real-space what the modeled object will look like. Just a few prominent examples: developed at the Fraunhofer Institute Virtual Design (see fig. 1.3.3.1) or mentioned already before Virtual Kitchen – tools

for interior designers who can visualize their sketches. They can change colors, textures and positions of objects, observing instantaneously how the whole surrounding would look like.

Figure 1.3.3.1. FhG Virtual Design (FhG IGD).

VR was also successfully applied to the modeling of surfaces [Brys92b, Butt92, Kame93]. The advantage of this technology is that the user can see and even feel the shaped surface under his/her fingertips. Although these works are pure laboratory experiments, it is to believe that great applications are possible in industry e.g., by constructing or improving car or aircraft body shapes directly in the virtual wind tunnel!

1.3.4.   Training and education

The use of flight simulators has a long history and we can consider them as the precursors of today's VR. First such applications were reported in late 1950s [Holl95], and were constantly improved in many research institutes mainly for the military purposes [Vinc93]. Nowadays they are used by many civil companies as well, because they offer lower operating costs than the real aircraft flight training and they are much safer (see fig. 1.3.4.1). In other disciplines where training is necessary, simulations have also offered big benefits. Therefore they were prosperously applied for determining the efficiency of virtual reality training of astronauts by performing hazardous tasks in the space [Cate95]. Another applications that allow training of medicine students in performing endosurgery [McGo94], operations of the eye [Hunt93, Sinc94] and of the leg [Piep93] were proposed in recent years (see fig. 1.3.4.2). And finally a virtual baseball coach [Ande93] has a big potential to be used in training and in entertainment as well.
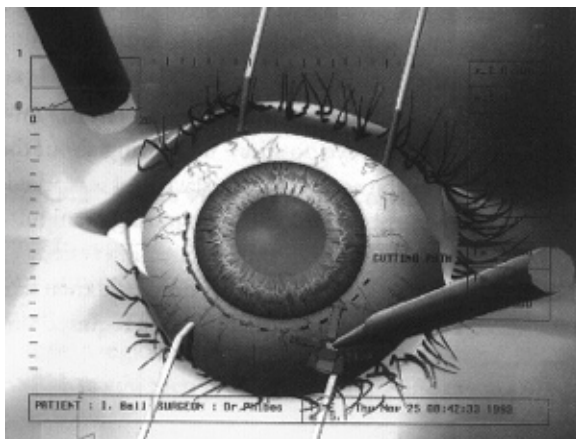
(a)   (b)

Figure 1.3.4.1. Advanced flight simulator of Boeing 777: (a) outside view, (b) inside view (from [Atla95]).

(a)   (b)

Figure 1.3.4.2. VR in medicine: (a) eye surgery (from [Hunt93]), (b) leg surgery (FhG IGD).

One can say that virtual reality established itself in many disciplines of human activities, as a medium that allows easier perception of data or natural phenomena appearance. Therefore the education purposes seem to be the most natural ones. The intuitive presentation of construction rules (virtual Lego-set), visiting a virtual museum, virtual painting studio or virtual music playing [Loef95, Schr95] are just a few examples of possible applications. And finally thanks to the enhanced user interface with broader input and output channels, VR allows people with disabilities to use computers [Trev94, Schr95].

1.3.5.   Telepresence and teleoperating

Although the goal of telerobotics is autonomous operation, a supervising human operator is still required in most of cases [Bola93]. Telepresence is a technology that allows people to operate in remote environments by means of VR user interfaces (see fig. 1.3.5.1 and 1.3.5.2). In many cases this form of remote control is the only possibility: the distant environment may be hazardous to human health or life, and no other technology supports such a high level of dexterity of operation. Figure 1.3.5.2 presents an example of master and slave parts of a teleoperating system.

The nanomanipulator project [Tayl93] shows a different aspect of telepresence – operating in environment, remote in terms of scale. This system that uses a HMD and force-feedback manipulation allows a scientist to see a microscope view, feel and manipulate the surface of the sample. As the same category, the mentioned already before eye surgery system [Hunt93], might be considered: beyond its training capabilities and remote operation, it offers the scaling of movements (by factor 1 to 100) for precise surgery. In fact it may be also called a centimanipulator.
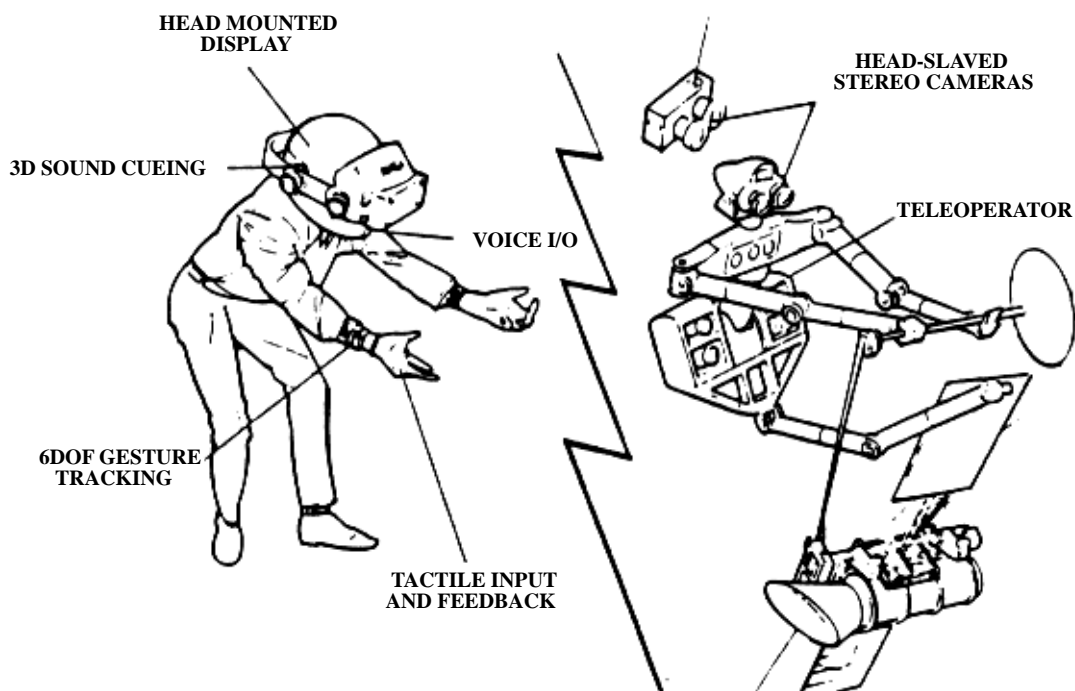

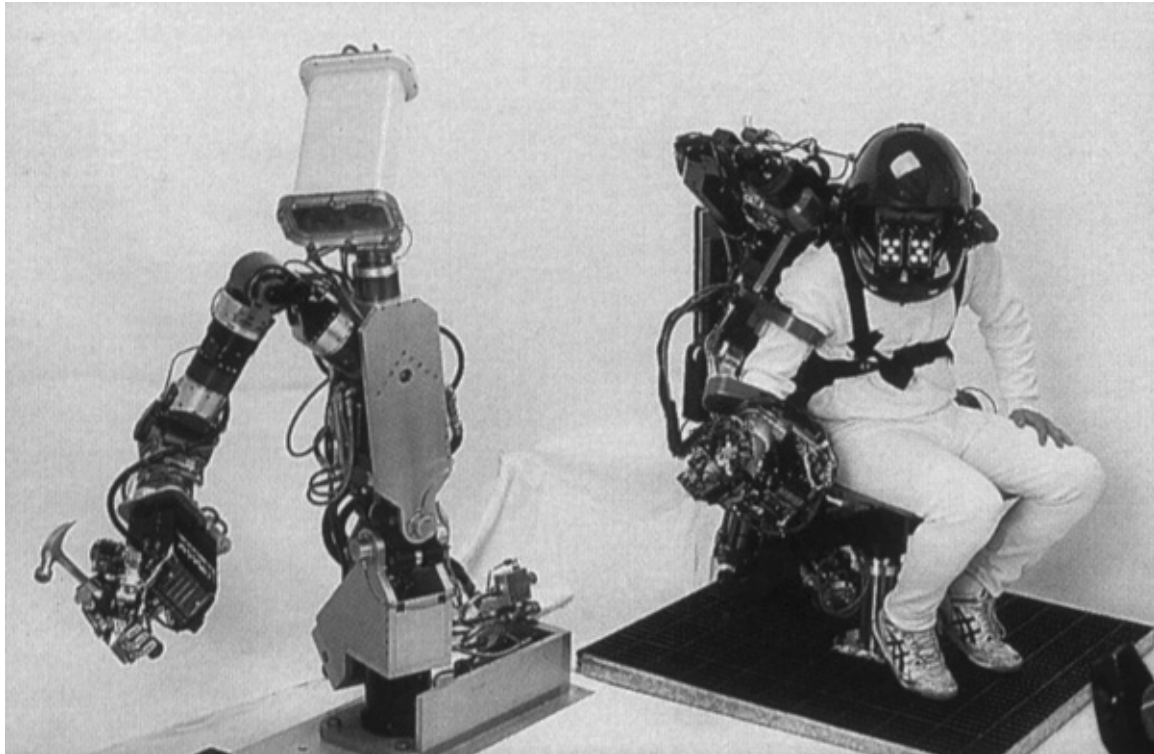**Figure 1.3.5.1.** The idea of teleoperating (adapted from [Bola93]).

Figure 1.3.5.2. The advanced teleoperation system developed at NOSC.

1.3.6. Cooperative working

Network based, shared virtual environments are likely to ease the collaboration between remote users. The higher bandwidth of information passing may be used for cooperative working. The big potential of applications in this field, has been noticed and multi-user VR becomes the focus of many research programs like NPSNET [Mace94, Mace95b], AVIARY [Snow94a] and others [Fahl93, Giga93b, Goss94]. Although these projects are very promising, their realistic value will be determined in practice.

Some practical applications, however, already do exist – just to mention a collaborative CO-CAD desktop system [Gisi94] that enables a group of engineers to work together within a shared virtual workspace. Other significant examples of distributed VR systems are training applications: in inspection of hazardous area by multiple soldiers [Stan94] or in performing complex tasks in open space by astronauts [Cate95, Loft95].

1.3.7. Entertainment

Constantly decreasing prices and constantly growing power of hardware has finally brought VR to the masses – it has found application in the entertainment. In last years W-Industry has successfully brought to the market networked multi-player game systems (see fig. 1.3.7.1). Beside these complicated installations, the market for home entertainment is rapidly expanding. Video game vendors like SEGA and Nintendo sell simple VR games, and there is also an

increasing variety of low-cost PC-based VR devices. Prominent examples include the Insidetrak (a simplified PC version of the Polhemus Fastrak), i-glasses! (a low cost see-through HMD) or Mattel PowerGlove.


Figure 1.3.7.1. VR in entertainment: Virtuality 1000DS from W-Industries (from [Atla95]).

Virtual reality recently went to Hollywood – Facial Waldo™ and VActor systems developed by SimGraphics allow to "sample any emotion on an actor's face and instantaneously transfer it onto the face of any cartoon character" [Dysa94]. The application field is enormous: VActor system has been used to create commercial impressive videos with ultra low cost: USD10 a second, where the today's industry standard is USD1,000 a second. Moreover, it may be used in live presentations, and might be also extended to simulate body movements.
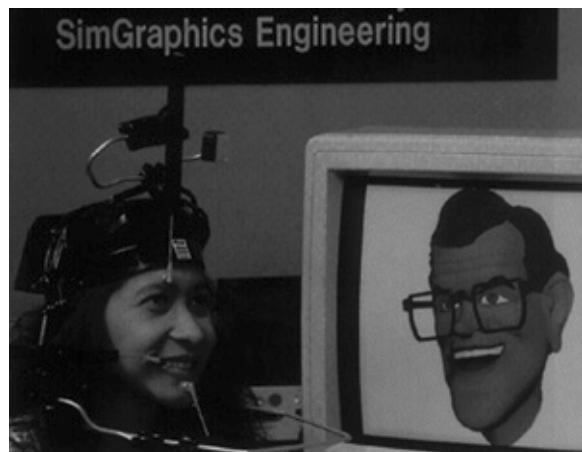
(a)   (b)

Figure 1.3.7.2. Facial animation systems from SimGraphics:
(a) VActor Xpression, (b) Facial Waldo™ (from [Dysa94]).

2. VR technology

2.1. A first look at VR applications: basic components

VR requires more resources than standard desktop systems do. Additional input and output hardware devices and special drivers for them are needed for enhanced user interaction. But we have to keep in mind that extra hardware will not create an immersive VR system. Special considerations by making a project of such systems and special software [Zyda93b] are also required. First, let us have a short look at the basic components of VR immersive applications:
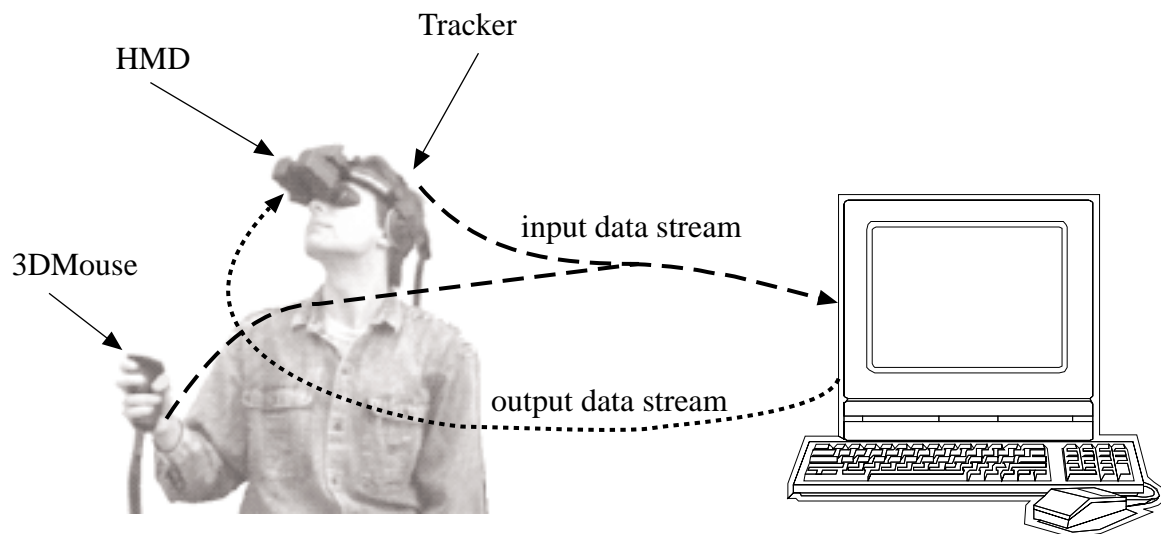

Figure 2.1.1. Basic components of VR immersive application.

Figure 2.1.1 depicts the most important parts of human-computer-human interaction loop fundamental to every immersive system. The user is equipped with a head mounted display, tracker and optionally a manipulation device (e.g., three-dimensional mouse, data glove etc.). As the human performs actions like walking, head rotating (i.e. changing the point of view), data describing his/her behavior is fed to the computer from the input devices. The computer processes the information in real-time and generates appropriate feedback that is passed back to the user by means of output displays.

In general: input devices are responsible for interaction, output devices for the feeling of immersion and software for a proper control and synchronization of the whole environment.

2.1.1. Input devices

Input devices determine the way a user communicates with the computer. Ideally all these devices together, should make user's environment control as intuitive and natural as possible – they should be practically invisible [Brys93e]. Unfortunately, the current state of technology is not advanced enough to support this, so naturalness may be reached in some very limited cases.

In most of cases we still have to introduce some interaction metaphors that may become a difficulty for an unskilled user.

2.1.2.   Output devices

Output devices are responsible for the presentation of the virtual environment and its phenomena to the user – they contribute to the generation of an immersive feeling at most. These include visual, auditory or haptic displays. As it is the case with input, the output devices are also underdeveloped. The current state of technology does not allow to stimulate human senses in a perfect manner, because VR output devices are far from ideal: they are heavy, low-quality and low-resolution. In fact most systems support visual feedback, and only some of them enhance it by audio or haptic information.

2.1.3.   Software

Beyond input and output hardware, the underlying software plays a very important role. It is responsible for the managing of I/O devices, analyzing incoming data and generating proper feedback. The difference to conventional systems is that VR devices are much more complicated than these used at the desktop – they require extremely precise handling and send large quantities of data to the system. Moreover, the whole application is time-critical and software must manage it: input data must be handled timely and the system response that is sent to the output displays must be prompt in order not to destroy the feeling of immersion.

2.2.   Human factors

As virtual environments are supposed to simulate the real world, by constructing them we must have knowledge how to "fool the user's senses" [Holl95]. This problem is not a trivial task and the sufficiently good solution has not yet been found: on the one hand we must give the user a good feeling of being immersed, and on the other hand this solution must be feasible. Which senses are most significant, what are the most important stimuli and of what quality do they have to be in order to be accepted by the user?

Let us start by examining the contribution of each of the five human senses [Heil92]:
- sight……………… 70 %
- hearing…………… 20 %
- smell ……………… 5 %
- touch……………… 4 %
- taste ……………… 1 %

This chart shows clearly that human vision provides the most of information passed to our brain and captures most of our attention. Therefore the stimulation of the visual system plays a principal role in "fooling the senses" and has become the focus of research. The second most

important sense is hearing, which is also quite often taken into consideration (see section 2.5.3 for details). Touch in general, does not play a significant role, except for precise manipulation tasks, when it becomes really essential (see section 2.3.3 and 2.5.2 for details). Smell and taste are not yet considered in most VR systems, because of their marginal role and difficulty in implementation.

The other aspects cannot be forgotten too: system synchronization (i.e. synchronization of all stimuli with user's actions), which contributes mainly to simulator sickness (see section 2.2.2 for details) and finally the design issues (i.e. taking into account psychological aspects) responsible for the depth of presence in virtual environments [Slat93, Slat94].

2.2.1. Visual perception characterization

As already mentioned before, visual information is the most important aspect in creating the illusion of immersion in a virtual world. Ideally we should be able to generate feedback equal to or exceeding the limits of the human visual system [Helm95]. Unfortunately today's technology is not capable to do so, hence we will have to consider many compromises and their implications on the quality of the resulting virtual environments.

Field of view

The human eye has both vertical and horizontal field of view (FOV) of approximately 180° by 180°. The vertical range is limited by cheeks and eyebrows to about 150°. The horizontal field of view is also limited, and equals to 150°: 60° towards the nose and 90° to the side [Heil92]. This gives 180° of total horizontal viewing range with a 120° binocular overlap, when focused at infinity (see fig. 2.2.1.1).
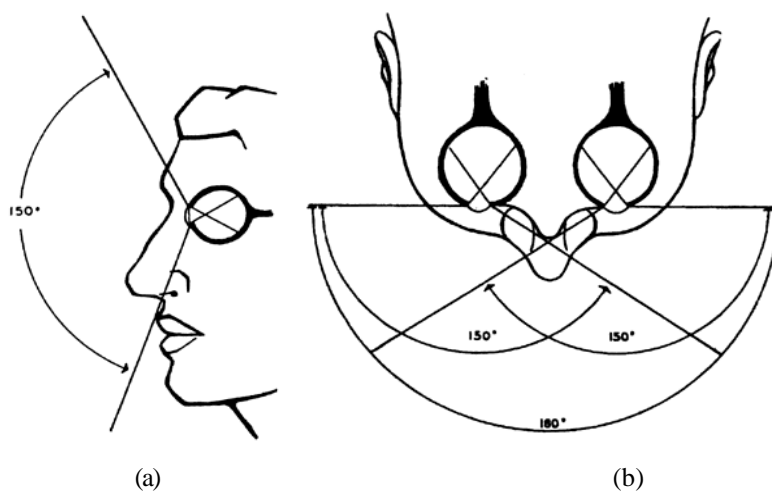

(a)   (b)

Figure 2.2.1.1. Human field of view: (a) vertical, (b) horizontal (from [Heil92]).

For a comparison: a 21" monitor viewed from the distance of 50cm covers approximately 48° of FOV, typical HMD supports 40° to 60° field of view. Some displays using wide field optics can support up to 140° of FOV.

Visual acuity

Visual acuity is defined as the sharpness of viewing. It is measured as the fraction of a pixel which spans one minute of arc horizontally [Cruz92]. Acuity changes for the different arc distances from the line of sight. For the objects that are reasonably lighted and lie on-axis (and therefore are projected onto the fovea – the part of retina that can resolve finest details in the image [Wysz82]) acuity is the best: the eye can resolve a separation of one minute of arc. The area of highest acuity covers a region of about two degrees around line of sight. Sharpness of viewing deteriorates rapidly beyond this central area (e.g., at 10° of the off-axis eccentricity it drops to ten minutes of arc [Helm95]).

Even the best desktop visual displays are far from achieving this quality – a 21" monitor with the resolution of 1280x1024 viewed from the distance of 50cm supports a resolution of 2.8 minutes of arc. Typical HMD offer much worse arc resolutions – they vary from four to six arc minutes.

Temporal resolution

Temporal resolution of the eye refers to the flickering phenomena perceived by humans, when watching a screen (e.g., CRT) that is updated by repeated impulses. Too low refresh rates, especially for higher luminance and big displays, causes the perception of flickering. To avoid this bad effect, a higher than the *critical fusion frequency* screen refresh rate (15Hz for small screens and low illumination levels to 50Hz for big screens and high illumination levels) must be used [Wysz82].

Today's technology supports this requirement fully – currently available at the market CRT monitors support 76Hz refresh-rates and more, and in case modern LCDs this problem does not occur because the screen is updated constantly.

Luminance and color

The human eye has a dynamic range of ten orders of magnitude [Wysz82] which is far more than any current available display can support. Moreover, none of the monitors can cover the whole color gamut. Therefore special color mapping techniques [Fers94] must be used to achieve possibly the best picture quality.

Depth perception

To generate depth information and stereoscopic images the brain extracts information from the pictures the eyes see and from the actual state of the eyes. This bits of information are called depth cues. All of the depth cues may be divided into two groups: *physiological* (like accommodation, convergence or stereopsis) and *psychological* (like overlap, object size, motion parallax, linear perspective, texture gradient or height in visual field) [Sche94]. All of them participate in generation of the depth information, but one must be careful not to provide contradictory cues to the user.

2.2.2.   Simulator sickness

There are potentially many sources of *simulator sickness*. Hardware imperfection may contribute to the generation of sickness feeling, because it fails to provide perfect stimuli to human senses. However, there are other crucial design issues: *system latency* and *frame rate variations*.

A number of studies investigated this problem, which indicates its meaning and weight. The studies of [Kenn92, Rega95] try to group and find out the intensity of all kind of maladies occurring in use of flight simulators and VR systems. The most frequently observed symptoms are: *oculomotor dysfunctions* (like eye strain, difficulty focusing, blurred vision), *mental dysfunctions* (like fullness of head, difficulty concentrating, dizziness) or *physiological dysfunctions* (like general discomfort, headache, sweating, increased salivation, nausea, stomach awareness or even vomiting) [Kenn92]. However, while these indications sound very frightening, it is important to mention that when 61% of the investigated subjects reported some symptoms of sickness, only 5% experienced moderate and 2% severe malady [Rega95].

Latency and synchronization

The success of immersive applications depends not only on the quality of images but also on the naturalness of the simulation. Desirable property of an intrinsic simulation is prompt, fluent and synchronized response of the system. The main component of latency is produced by rendering [Mine95b, Mazu95a], consequently frame update rates have the biggest effect on the sense of presence and efficiency of performed tasks in VEs [Brys93d, Paus93a, Ware94, Barf95]. Low latencies (below 100ms) have little effect on performance of flight simulators [Card90] and frame rates of 15Hz seem to be sufficient to fulfill the sense of presence in virtual environments [Barf95]. Nevertheless higher values (up to 60Hz) are preferred [Deer93b], when performing fast movements or when perfect registration (e.g., in augmented reality) is required [Azum94].

What are the physiological causes of the latency induced simulator sickness? One hypothesis is that sickness arises from a mismatch between visual motion cues and the

information that is sent to brain by the vestibular system [Helm95]. This might be the case for both: motion based VR systems and static ones. This hypothesis seems to be correct because the human individuals without functioning vestibular system are not subject to simulator sickness [Eben92].

Frame rate variations

Non-constant frame rates may have a negative influence on the sense of presence and can also cause simulator sickness. The humans are simply adapting to the slow system responses and when the update does not come at the expected (even delayed) time-stamp our senses and brain are disoriented. Therefore constant frame rate algorithms are developed [Funk93] (see also section 2.4).

2.3. VR input devices

2.3.1. Position and orientation tracking devices

The absolute minimum of information that immersive VR requires, is the position and orientation of the viewer's head, needed for the proper rendering of images. Additionally other parts of body may be tracked e.g., hands – to allow interaction, chest or legs – to allow the graphical user representation etc. Three-dimensional objects have six *degrees of freedom* (DOF): position coordinates (*x*, *y* and *z* offsets) and orientation (*yaw*, *pitch* and *roll* angles for example). Each tracker must support this data or a subset of it [Holl95]. In general there are two kinds of trackers: those that deliver *absolute* data (total position/orientation values) and those that deliver *relative* data (i.e. a change of data from the last state).

The most important properties of 6DOF trackers, to be considered for choosing the right device for the given application are [Meye92, Bhat93, Holl95]:

- **update rate** – defines how many measurements per second (measured in Hz) are made. Higher update rate values support smoother tracking of movements, but require more processing.
- **latency** – the amount of time (usually measured in ms) between the user's real (physical) action and the beginning of transmission of the report that represents this action. Lower values contribute to better performance.
- **accuracy** – the measure of error in the reported position and orientation. Defined generally in absolute values (e.g., in mm for position, or in degrees for orientation). Smaller values mean better accuracy.
- **resolution** – smallest change in position and orientation that can be detected by the tracker. Measured like accuracy in absolute values. Smaller values mean better performance.

- **range** – working volume, within which the tracker can measure position and orientation with its specified accuracy and resolution, and the angular coverage of the tracker.

Beside these properties, some other aspects cannot be forgotten like the ease of use, size and weight etc. of the device. These characteristics will be further used to determine the quality and usefulness of different kinds of trackers.

Magnetic trackers

Magnetic trackers are the most often used tracking devices in immersive applications. They typically consist of: a static part (*emitter,* sometimes called a *source*), a number of movable parts (*receivers,* sometimes called *sensors*), and a control station unit. The assembly of emitter and receiver is very similar: they both consist of three mutually perpendicular antennae. As the antennae of the emitter are provided with current, they generate magnetic fields that are picked up by the antennae of the receiver. The receiver sends its measurements (nine values) to the control unit that calculates position and orientation of the given sensor. There are two kinds of magnetic trackers that use either alternating current (AC) or direct current (DC) to generate magnetic fields as the communication medium [Meye92].

The continuously *changing* magnetic field generated by AC magnetic trackers (e.g., 3Space Isotrak, Fastrak or Insidetrak from Polhemus) induces currents in coils (i.e. antennae) of the receiver (according to Maxwell's law). The bad side-effect is the induction of eddy currents in metal objects within this magnetic field. These currents generate their own magnetic fields that interfere and distort the original one, which causes inaccurate measurements. The same effect appears in vicinity of ferromagnetic objects.

DC trackers (e.g., Bird, Big Bird or Flock of Birds from Ascension) transmit a short series of *static* magnetic fields in order to avoid the eddy current generation. Once the field reaches a steady state (eddy currents are still generated but *only* at the beginning of measurement cycle) the measurement is taken with the help of flux-gate magnetometers [Asce95b]. To eliminate the influence of the Earth's magnetic field, this constant component (measured when the transmitter is shut off) is subtracted from the measured values. Although DC trackers eliminate the problem of eddy current generation in metal objects, they are still sensitive to ferromagnetic materials [Asce95b].

Figure 2.3.1.1. Emitter and receiver units of Polhemus Fastrak.

Under optimal conditions (lack of any kind of magnetic interference) magnetic trackers have a relatively good performance. For illustration we give a technical description of two commonly used products – Polhemus Fastrak [Polh93] and Ascension Flock of Birds [Asce95a]:

Tracker	Max. # of sensors	Max. range (m)	Lag (ms)	Max. update rate (Hz)	Accuracy (RMS)	Resolution at distance
Polhemus Fastrak	4	3.05	4	120 / # of sensors	0.8 mm 0.15°	5e-03mm per mm 0.025°
Ascension Flock of Birds	30	1	< 10	144	2.54 mm 0.5°	0.5mm at 30cm 0.1° at 30cm

Table 2.3.1.1. Technical data of magnetic trackers.

Advantages:

- sensors are small, light and handy
- have no line-of-sight constraint
- non-sensitive to acoustic interference
- relatively high update rates and low latency
- off-the-shelf availability

Disadvantages:

- since magnitude of magnetic field strongly decreases with distance from the emitter, the working volume of magnetic trackers is very limited and the resolution is getting worse as the emitter-receiver distance is growing.
- magnetic field is subject to distortion, caused by metal objects inside of it (AC trackers only). Moreover, any external magnetic field generated e.g., by CRT displays or by ferromagnetic objects in vicinity (both AC and DC trackers) may cause additional distortion that leads to inaccurate measurements.

Acoustic (ultrasonic) trackers

Acoustic trackers use ultrasonic waves (above 20kHz) for determining the position and orientation of object in space. As the use of sound allows the determination of relative distance between two points only, multiple emitters (typically three) and multiple receivers (typically three) with known geometry are used to acquire a set of distances to calculate position and orientation [Meye92]. There are two kinds of acoustic trackers – they either use time-of-flight (TOF) or phase-coherent (PC) measurements to determine the distance between a pair of points. TOF trackers (e.g., Logitech 6DOF Ultrasonic Head Tracker, Mattel PowerGlove) measure the flight time of short ultrasonic pulses from the source to the sensor. PC trackers (for example used by I. Sutherland in 1968! [Suth68]) compare the phase of a reference signal with the phase of the signal received by the sensors. The phase difference of 360° is equivalent to the distance of one wavelength. The difference between two successive measurements of phases allows to compute the distance change since the last measurement. As this method delivers relative data (so the error tends to accumulate with time), development of PC trackers was relinquished.

The typical working parameters of acoustic TOF trackers (taken from the Logitech 6DOF specification – see fig. 2.3.1.2) are:

- range ……………1.5m and 100° cone of angular coverage
- update rate ……….50Hz
- lag ………………30ms
- accuracy………….2% of distance from source and 0.1° of orientation
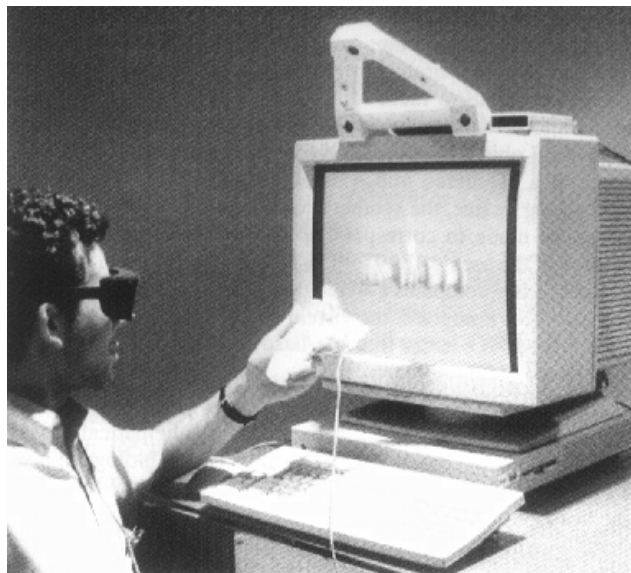

Figure 2.3.1.2. Logitech 6DOF Ultrasonic Tracker (from [Deer92]).

Advantages (of TOF trackers):

- light and small
- relatively cheap (from USD1000)
- do not suffer from magnetic interference

Disadvantages (of TOF trackers):

- line-of-sight restriction
- suffer from acoustic interference – noise or echoes may lead to inaccurate measurements
- low update rates

Optical trackers

There are many different kinds and configurations of optical trackers. Generally we can divide them into three categories [Meye92]:

- **beacon trackers** – this approach uses a group of beacons (e.g., LEDs) and a set of cameras capturing images of beacons' pattern. Since the geometries of beacons and detectors are known, position and orientation of the tracked body can be derived [Wang90, Ward92]. There are two tracking paradigms: *outside-in* and *inside-out* (see fig. 2.3.1.3).
- **pattern recognition** – these systems do not use any beacons – they determine position and orientation by comparing known patterns to the sensed ones [Meye92, Reki95]. No fully functioning systems were developed up to now. A through-the-lens method of tracking may become a challenge for the developers [Thom94].
- **laser ranging** – these systems transmit onto the object the laser light that is passed through a diffraction grating. A sensor analyzes the diffraction pattern on the body's surface to calculate its position and orientation.

For all these systems the accuracy decreases significantly as the distance between sensors and tracked objects grows [Meye92].

Advantages:

- high update rates (up to 240Hz [Holl95]) – in most of cases limited only by the speed of the controlling computer
- possibility of the extension to the large working volumes [Wang90, Ward92]
- not sensible to the presence of metallic, ferromagnetic objects; not sensible to acoustic interference
- relatively good accuracy: magnitude orders of about 1mm and 0.1˚

Disadvantages:

- line-of-sight restriction
- ambient light and infrared radiation may influence the performance
- expensive and very often complicated construction
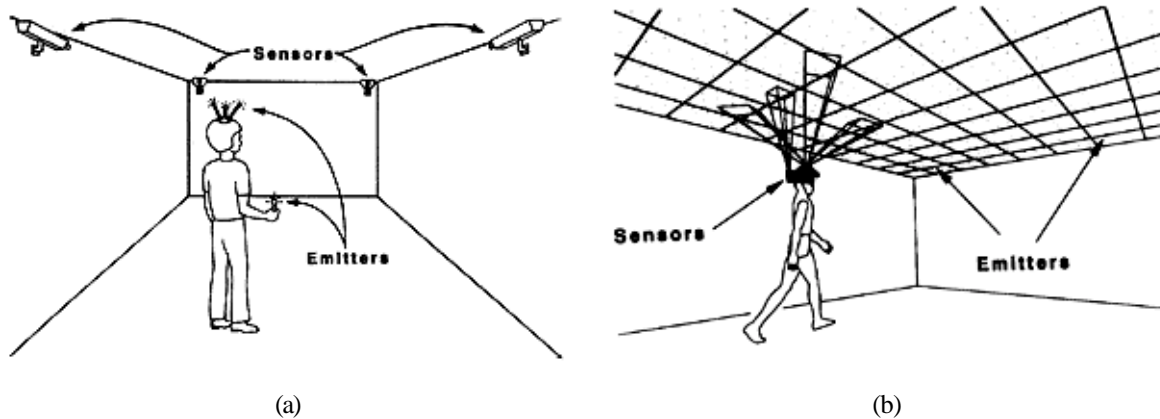- difficulties to track more than one object in one volume

(a)   (b)

Figure 2.3.1.3. Beacon trackers: (a) outside-in and (b) inside-out tracking paradigms (UNC).

Mechanical trackers

A mechanical linkage of a few rigid arms with joints between them is used to measure position and orientation of a free point (attached to the end of the structure) in relation to the base. The angles at the joints are measured with the help of gears or potentiometers, which combined with the knowledge of linkage construction allows to derive the required position and orientation values (see fig 2.3.1.4). A prominent example of a mechanical tracking device is the BOOM (Binocular Omni-Oriented Monitor) developed by Fake Space Labs (see fig. 2.3.1.5).
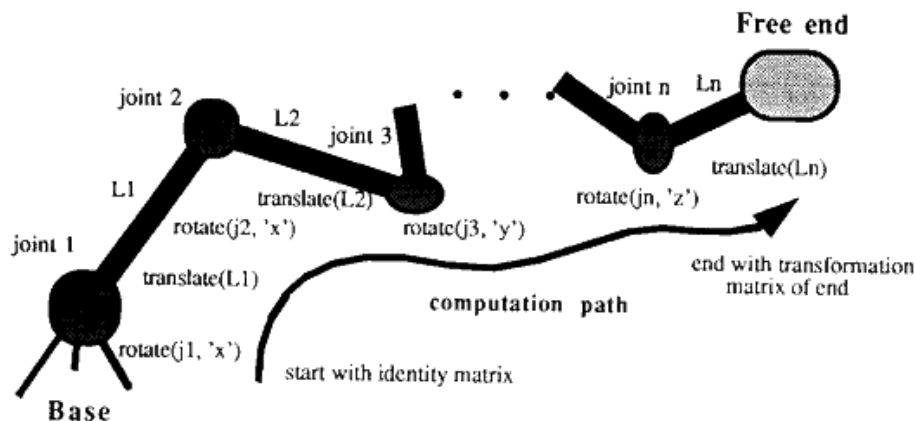

Figure 2.3.1.4. The idea of mechanical linkage (from [Brys93e]).

Figure 2.3.1.5. Mechanical tracking device: BOOM from Fake Space Labs.

Advantages:

- very accurate

- immune to all kind of interferences (unless mechanical obstacles)

- high update-rates (up to 300Hz)

- may support force-feedback

Disadvantages:

- not full freedom of movements due to the mechanical linkage

- small working volume (about one cubic meter)

- only one object can be tracked in one volume

2.3.2.   Eye tracking

Head tracking allows proper rendering of images from the user's point of view. The advantage of the head tracking is that motion parallax cue can be provided, which improves the depth perception. One more important aspect can be taken into account: the visual acuity of the eye changes with the arc distance from the line-of-sight. It means that image does not need to have equal resolution and quality over the whole display area. Objects that lie far the line-of-sight can be represented coarsely, because the user will not notice it. Consequently, this may lead to the dramatically decrease of rendering costs [Levo90, Funk93, Redd95]. Therefore eye-tracking techniques may be incorporated to determine the gaze direction [Youn75, Stam93].

In general, most important eye-tracking technologies can be grouped as follows:

- **limbus tracking** – the sharp boundary between iris and sclera (limbus) can be easily identified. The infrared LEDs and photo-transistors are mounted on the user's glasses to monitor infrared spots reflections from the iris and sclera in order to determine the gaze direction. This technique offers good accuracy (1˚ to 3˚), but limits vertical eye movements (by extreme vertical eye movements limbus is partially obscured by eye-lids what hinders exact measurement). It is used by e.g., the NAC Eye Mark eye tracker (see fig. 2.3.2.1).

- **image tracking** – uses a video camera and image processing techniques to determine the gaze direction. This technology offers good accuracy – typically about 1˚ (used by e.g., ISCAN, Applied Science Labs 4000 SU-HMO [Holl95]).

- **electro-oculography (EOG)** – uses the electrodes placed beside the eyes to measure the standing potential between cornea and retina. Typically, the recorded potentials are very small: in the range of 15μV to 200μV. This approach has a questionable worth because it is susceptible to external electric interference and muscle-action potentials.

- **corneal reflection** – uses photo-transistors to analyze a reflection of collimated beam of light from the convex cornea surface. This approach offers relatively good accuracy (0.5˚ to 1˚), but it needs complex calibration, covers relatively small eye-movement area and is sensitive to variations in cornea shape variations, tear fluids and corneal astigmatism.
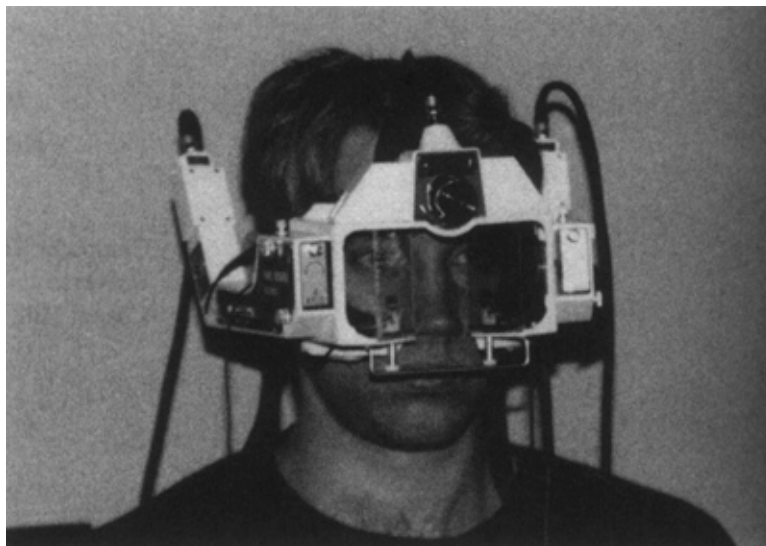

Figure 2.3.2.1. NAC Eye Mark eye tracker (from [Levo90]).

2.3.3. 3D input devices

Beside trackers that capture user's movements, many other input devices were developed to make human-computer interaction easier and more intuitive. For full freedom of movements

three-dimensional input devices seem the most natural. Attached to our body or hand-held, they are generally used to select, move, modify etc. virtual objects. This chapter presents a broad overview of most important of these devices.

3D Mice and Bats

This basic and simple user interaction tool is in general a joystick-like 6DOF device that can be moved in space by hand. It is equipped with a tracker sensor to determine its position/orientation and a few buttons that may trigger some actions [Ware90a]. Some 3D mice may be equipped with a thumbball for additional movement control.

Gloves

Gloves are 3D input devices that can detect the joint angles of fingers. The measurement of finger flexion is done with the help of fiber-optic sensors (e.g., VPL DataGlove), foil-strain technology (e.g., Virtex CyberGlove) or resistive sensors (e.g., Mattel PowerGlove). The use of gloves allows the user richer interaction than the 3D mouse, because hand gestures may be recognized and translated into proper actions [Mine95a]. Additionally gloves are equipped with a tracker that is attached to the user's wrist to measure its position and orientation.

(a)   (b)
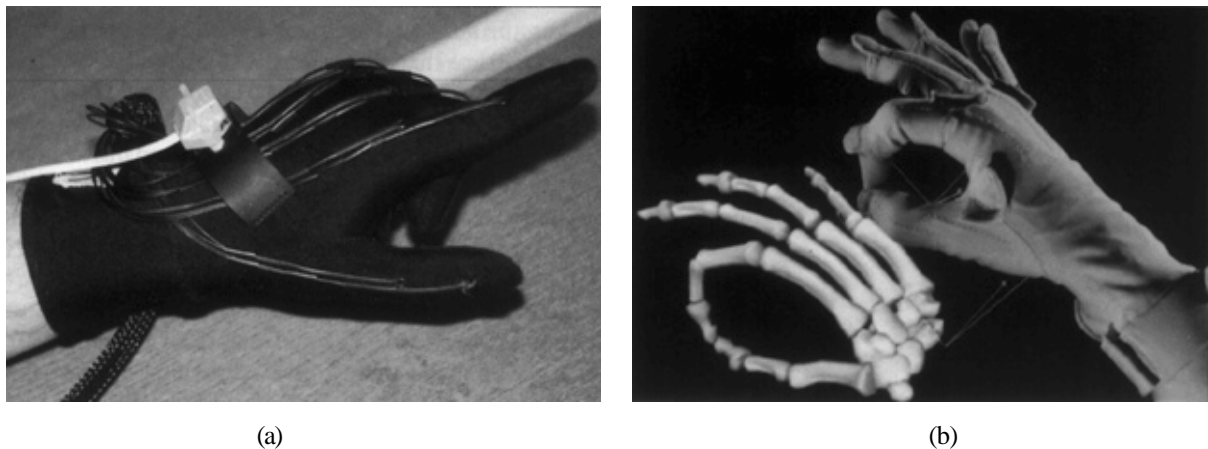
Figure 2.3.3.1. Gloves: (a) VPL DataGlove, (b) Virtex CyberGlove (from [Stur94]).

An obvious extension of the data glove is a data suit that covers the whole body of the user. The first step in this direction is capturing of the whole body movements with minimal number of sensors [Badl93a]. In last few years more and more attention was paid to such devices, and there are already commercial data suits on the market like e.g., the VPL DataSuit. An example of application of the body tracking technology is the real-time animation of virtual actors in film industry.

Dexterous manipulators

Some applications (e.g., teleoperation, surgery) require extremely precise control. The data gloves are very often not sufficient to fulfill these demands and therefore many dexterous manipulators were developed, for example: the Master Manipulator [Iwat90], the Dexterous Hand Master (DHM) from Utah University [Rohl93a, Rohl93b], further developed by EXOS (see fig. 2.3.3.2a) or the DHM from NOSC (see fig. 2.3.3.2b). The Master Manipulator (see fig. 2.5.2.1a) is a relatively simple device – it supports only 9DOF control and force feedback (see section 2.5.2 for details). It uses potentiometers to measure bending angles. Dexterous Hand Masters are much more elaborated devices: they can trace three joints angles for each finger (4DOF for each finger which makes total 20DOF for the whole hand). Moreover, they guarantee high precision measurement of bending angles (error magnitude order of $1°$ in contrast to $5°$-$10°$ in case of gloves [Stur94]) thanks to Hall-effect [Tipl91] sensors.

(a)   (b)

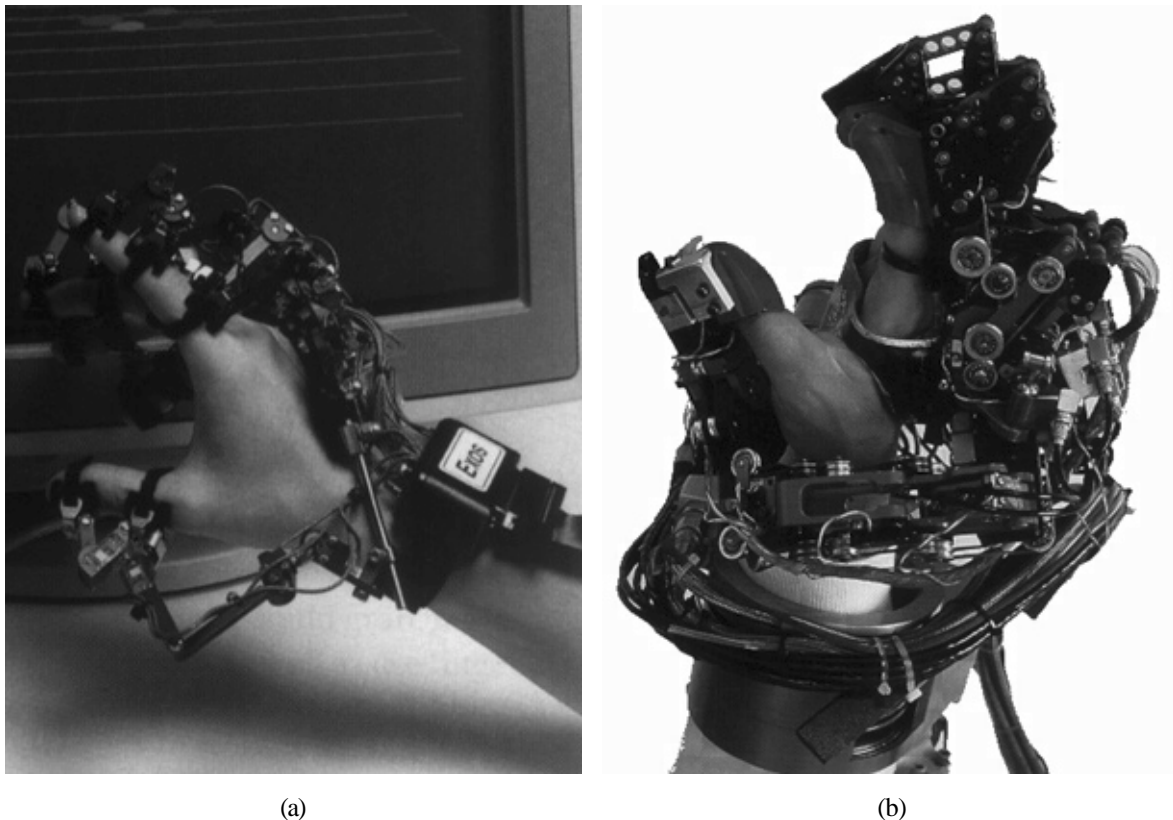**Figure 2.3.3.2.** Dexterous manipulators: (a) EXOS Dexterous Hand Master (from [Stur94]),

(b) NOSC Dexterous Hand Master.

2.3.4.   Desktop input devices

Beside sophisticated and expensive three-dimensional input devices, many special desktop tools are very popular. The do not give so good and intuitive control like 3D devices and decrease the immersion feeling, but are handy, simple in use and relatively cheap.

SpaceBall

SpaceBall is a simple 6DOF input device (see fig. 2.3.4.1). The user can grab the ball with his/her hand and manipulate it – the device measures translation forces and rotation torques of the ball and sends this data to the host computer. Additional buttons are built-in to enhance the interaction possibilities.
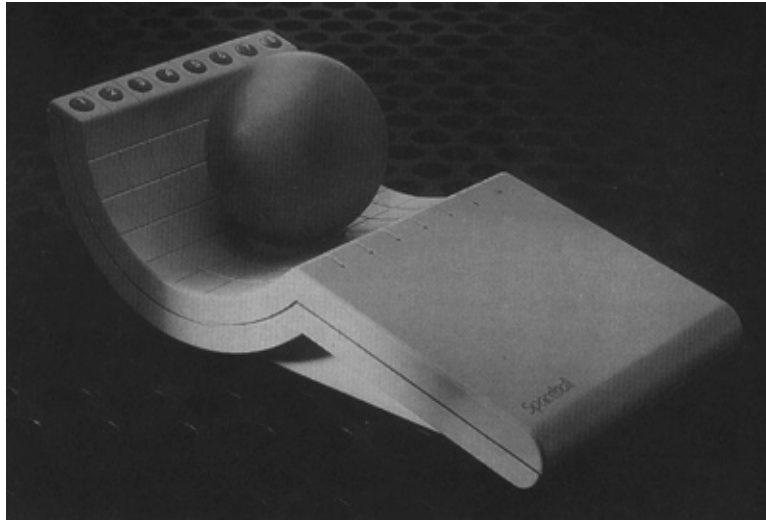
Figure 2.3.4.1. SpaceBall – desktop 6DOF input device (from [Vinc95]).

CyberMan

CyberMan is an extension of typical two-dimensional mouse (see fig. 2.3.4.2). It supports 6DOF input. With a help of small motor it can simulate quasi-haptic feedback: the part of these device kept in hand can vibrate to indicate a collision, or force-feedback. CyberMan is most often used in computer games.

Figure 2.3.4.2. CyberMan from Logitech – desktop 6DOF input device.

2D input devices

Many desktop systems are equipped only with standard 2D input mice. They do not support so intuitive control of three-dimensional objects like any of previously described 6DOF manipulators, but are very popular, wide-spread and cheap. Nevertheless, to allow the user a relatively easy way of manipulation of 3D objects, software virtual controllers were implemented. A virtual sphere controller – a simulation of 3D trackball [Chen88] and other tools [Niel86] support easy, interactive rotating and positioning of three-dimensional objects with the use of simple 2D desktop mouse (for more advanced virtual controls – 3D widgets see section 2.4.2).

2.4.   VR worlds: modeling, interaction and rendering

Every VR application must be effective by means of performance and interaction. This requirement can be only fulfilled when all system parts – input, interaction and output – are properly integrated one with the other. Nowadays, even the best hardware cannot support this by itself – it needs software assistance for precise control, resources management and synchronization.

2.4.1.   Construction of virtual worlds

Construction of virtual environments involves many different aspects that were not present in standard computer graphics. The biggest challenge to trade is performance vs. natural look and behavior. As already mentioned before, these requirements are contradictory: more convincing models and better physical simulation demand more resources, thereby increasing computational cost and affecting overall performance. Many different kinds of models representing virtual worlds can be imagined: from simple models like a single unfurnished room, to extremely complex ones like a the whole city with many buildings containing a lot of chambers, each modeled with high amount of detail. While it is trivial to display a simple model with adequate performance, but rendering millions of polygons would hinder interactive frame-rates, even if we were able to load the whole scene into main memory. Hence it will never be technically possible (the faster the hardware, the finer and more complex models will be), we must develop dedicated data structures and algorithms allowing to produce the best image quality with acceptable cost.

Data structures and modeling

For huge scenes containing millions of polygons, the challenge is to identify the relevant (potentially visible) portion of the model, load data into memory and render it at interactive frame-rates. In many cases it may still happen that the number of polygons of all visible objects dramatically exceeds rendering capabilities. Therefore the other important aspect of the data

structure construction is *level-of-detail* (LOD) definition (see fig. 2.4.1.1). Due to the perspective projection distant objects appear smaller on the screen that the close ones (see fig. 2.4.1.2). In the extreme case they may cover as little as one pixel! In this situation it does not make sense to render them with the highest possible geometric resolution, because the user will not notice it. Nevertheless, when the same objects are closer to the user they must be rendered with a high resolution in order to let him/her see all the details.

(a)   (b)

Figure 2.4.1.1. Multiple levels-of-detail of the same object: (a) low LOD, (b) high LOD (from [Funk93]).
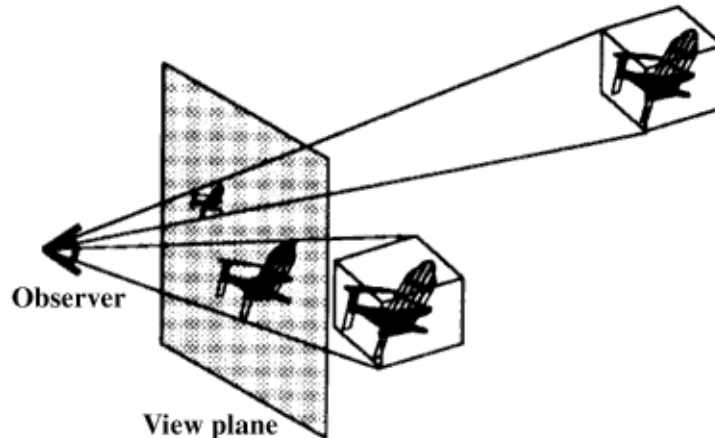
Figure 2.4.1.2. Distant objects appear smaller on the screen than the close ones (from [Funk93]).

To achieve the best image quality at interactive frame rates, several approaches may be used [Tell91, Funk92, Funk93, Falb93, Maci95, Scha96a]:

- **hierarchical scene database** – the scene is represented as a set of objects. Each object of the scene is described with multiple LODs that represent different accuracy of object representation (and contain different numbers of polygons). In extreme case objects can be represented by one textured polygon [Maci95].

- **visibility precomputation (analysis)** – the whole visual database is spatially subdivided into cells connected by portals. The visibility analysis is performed on such a prepared model in two phases: the preprocessing phase (determination of *cell-to-cell* and *cell-to-object* visibility) and during the walkthrough phase (determination of *eye-to-cell* and *eye-to-object* visibility). To improve the performance of this process the splitting planes are chosen along the major obscuring elements e.g., walls, floors, ceilings or door frames [Funk92] (see fig. 2.4.1.3).

- **memory management** – if the whole scene cannot be loaded into the main memory, special algorithms for swapping in the relevant parts must be used. The loading of objects from the disk can take relatively much time, so prediction of objects that might be potentially visible in the near future has to be done and loading should start in advance (*prefetching*), in order to avoid waiting in the rendering phase.

- **constant frame-rate rendering** – after all the potentially visible objects were determined in the visibility preprocessing phase, it still may happen that not all of them can be rendered with their highest resolution. To provide the best quality of the image within a given time, the selection of LOD and rendering algorithm for each object must be performed. Several properties of objects should be taken into account e.g., size on the screen, importance for the user, focus (position on the screen, where he/she is looking) or motion (for fast moving objects we cannot see many details) [Funk93]. As the graphics pipeline in most graphical systems is used, the proper load balancing in each of the stages must be taken into account [Funk93, Sowi95].
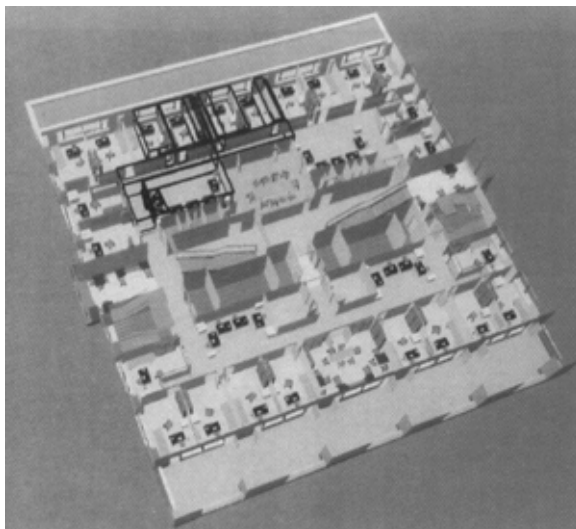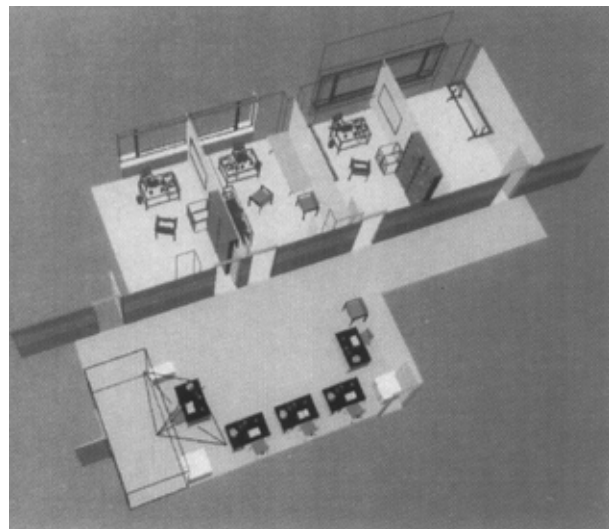
| (a) | (b) |

Figure 2.4.1.3. Data pruning: (a) before and (b) after visibility computation (from [Funk92]).

The demand for highly detail scenes has grown rapidly in the last years, so labor-intensive, manual creation and processing became impractical. Automatic generation and processing of models offers great possibilities: for example, creation of objects from multiple stereoscopic images was proposed recently [Koch94]. Moreover, techniques that can generate automatically multiple levels-of-detail from one high resolution polygonal representation are very helpful, because they can accelerate the creation of hierarchical scene databases for interactive walkthrough applications [Turk92, Ross93a, Heck94, Scha95a].

Physical simulation

Virtual reality may be a clone of physical (real) reality or a kind of closer not defined (cyber)space that has it own rules. In both of these cases a simulation of the environment has to be done. In case of newly defined cyberspace the task is relatively easy – we can invent new laws or use simplified physics. The real challenge is to simulate the rules of physics precisely, because they are very complex phenomena: dynamics of objects, electromagnetic forces, atomic forces etc. For the human-computer interaction purposes a subset of them has to be considered. Newton's laws are the basis when simulating movements, collisions and force-interaction between objects [Vinc95].

The simulation, collision detection [Zyda93c, Fang95] and animation of autonomous objects, may be a very complex and time-consuming task, so other approaches must be applied than in standard (i.e. non-real time) animation. The simulation process that manages the behavior of the whole environment (including interaction between different users) should be run in the "background" – decoupled from the user's interaction [Shaw92a, Shaw93b] in order to support the full performance. The updates between these application parts are realized by means of asynchronous operations.

The construction and maintaining of physically based, multi-user and therefore distributed virtual environments is not an easy task. Beside usual expectations – high efficiency support for lag minimization – it demands hardware independence, flexibility and high-level paradigms for easy programming, maintaining and consistent user interface. A few prominent examples of VE toolkits and systems (i.e. VE shells) are: MR (Minimal Reality) [Shaw93a, Shaw93b], NPSNET [Zyda92b, Mace94, Mace95b], AVIARY [Snow93, Snow94a] or DIVE [Carl93a, Carl93b].

2.4.2. Interacting with virtual worlds

The ultimate VR means that no user interface is needed at all – every interaction task should be as natural as in (real) reality. Unfortunately this is not possible today because of technical problems. However, many techniques may be used to enhance the interaction model [Bala95], but they still use some metaphors to make human-computer dialog easier.

Interaction paradigms in 3D

The human hand is most dexterous part of our body – in reality we use it (or both of them) intuitively to perform a variety of actions: grabbing or moving objects, typing, opening doors, precise manipulations etc. The most natural way of interacting with the computer is probably by using the hand. Therefore the majority of already introduced in section 2.3 VR input devices are coupled to our palm. They represent a broad variety of levels of advance, complexity and price, so for different applications other devices and modes of interaction are used. Basic interaction tasks in VEs are: camera control (for observation), navigation, object manipulation and information access.

Camera control

Observation of the scene is essential to the user, because it provides information about his/her location in virtual world. Intuitive camera control is fundamental – it is responsible for the immersion feeling. In the ideal case, where head-tracking is available the point of view is directly set by rotating and moving the user's head. This model is without doubt the most convincing one, but on the other hand, not every system supports head-tracking capabilities. Therefore other camera control models were developed [Ware90b] for non-immersive applications. Camera movements can be steered with e.g., desktop spaceball devices. Two control metaphors have been proven to be helpful in observing virtual worlds, and can be changed during the interaction task according to the user needs:

- **eyeball in hand** – with this metaphor the user has to imagine that the spaceball represents the eye he/she is watching the scene with. The user can intuitively translate and rotate it (full 6DOF control) to change the viewing point and direction. This metaphor is very useful when the user is immersed "inside" of the scene (i.e. the scene surrounds him/her).
- **scene in hand** – with this metaphor the camera has the constant position and orientation, and the whole scene can be manipulated (i.e. rotated and translated). This metaphor is very useful, in the case when the user watches the whole scene (or some specific objects of it) from "outside". This is a natural way of observing from different sides the objects that appear small and therefore can be "kept in hand" (it is easier to rotate them, than to walk them around).

Navigation

In many cases, user may want to explore the whole (very often big) environment. Walking over long distances cannot be realized so easily, because of the limited tracking range. Therefore an appropriate transport medium is needed. In general, with the help of some input devices we can define the motion of our body in virtual space. Depending on the type of application this may be

either *driving* (in 2D space) or *flying* (in 3D space). The principles of these navigation paradigms are however the same [Robi93, Mine95a, Vince95]:

- **hand directed** – position and orientation of hand determines the direction of motion in virtual world. In this approach different modes can be incorporated to specify the required direction: *pointing* or *crosshair* mode. In the first case, moving is performed along a line the pointing finger determines. In the second one, a cursor (crosshair) is attached to the user's hand and the line between the eye and cursor defines the moving direction.

- **gaze directed** – looking direction (head orientation) specifies the line of movement. It is a relatively easy metaphor for an unskilled user but hinders "looking around" during the motion because direction of motion is always attached to the gaze direction.

- **physical controls** – input devices like joysticks, 3D mice, spaceballs are used to specify the motion direction. They allow precise control, but often the lack of correspondence between device and motion may be confusing. However, construction of special devices for certain applications may increase the feeling of immersion (e.g., steering wheel for driving simulation).

- **virtual controls** – instead of physical devices, virtual controls can be implemented. This approach is hardware independent and therefore is much more flexible, but interaction may be difficult because of lack of haptic feedback.

All these modes are based on the principle of steering a virtual vehicle through the space. The user sitting inside of this vehicle can determine not only the direction but the speed and acceleration of movements (e.g., pressing buttons, or by hand gestures). Moreover, he/she can still rotate and move his/her head in his/her local coordinate system. The higher level navigation models can be also incorporated:

- **teleporting** – the moving through the virtual world is realized with the help of autonomous elevator-like devices or portals that once entered move the user to the specified point of space. The obvious extension of this mode is *goal driven* navigation, where the user can choose the target with a help of virtual menu [Jaco93] or a sensitive map.

- **world scaling** – the distances in virtual world may be dynamically changed according to the user's needs. For example we can scale the world down and move to the desired position (e.g., make one step one thousand kilometers long) and scale the world back to the original size. The scaling of the model up can be also performed to allow the user precise control (e.g., nanomanipulation [Tayl93] or eye surgery [Hunt93]).

Selection (object picking)

To perform any action that causes the change of virtual world state, the user must first select the object that will be the subject of manipulation. There are two primary selection

techniques [Mine95a]: *local* and *at-a-distance*. In the local mode, selecting is done when the collision between user's hand represented with e.g., 3D cursor and object is detected. In the at-the-distance mode, a ray is shot in to the scene to pick the object. The selection-ray can be determined by hand's orientation or gaze direction. An alternative selection-mode may be done by choosing entries from the virtual menu [Jaco93].

Manipulation

Once the object is selected (which is signaled by e.g., highlighting it on the screen) the user must be able to manipulate it: move, rotate, scale, change attributes etc. This can be achieved by defining special button presses, hand gestures [Stur93] or menu entries that choose a proper tool. These tools can be driven by physical input devices like mice, joysticks, sliders, gauges, hand position tracking [Ware90a] or even by a nose-gesture interface [Henr92] :-).

A new paradigm of the 3D user interface and its use in the modeling process – 3D widgets (see fig. 2.4.2.1) were proposed lately [Broo92a]. Widgets encapsulate the geometry and behavior, and therefore are flexible virtual controls that can be elaborated individually for the application needs. Currently these widgets are used in a desktop system but porting them into full immersive VR application seems to be straightforward.

(a)   (b)
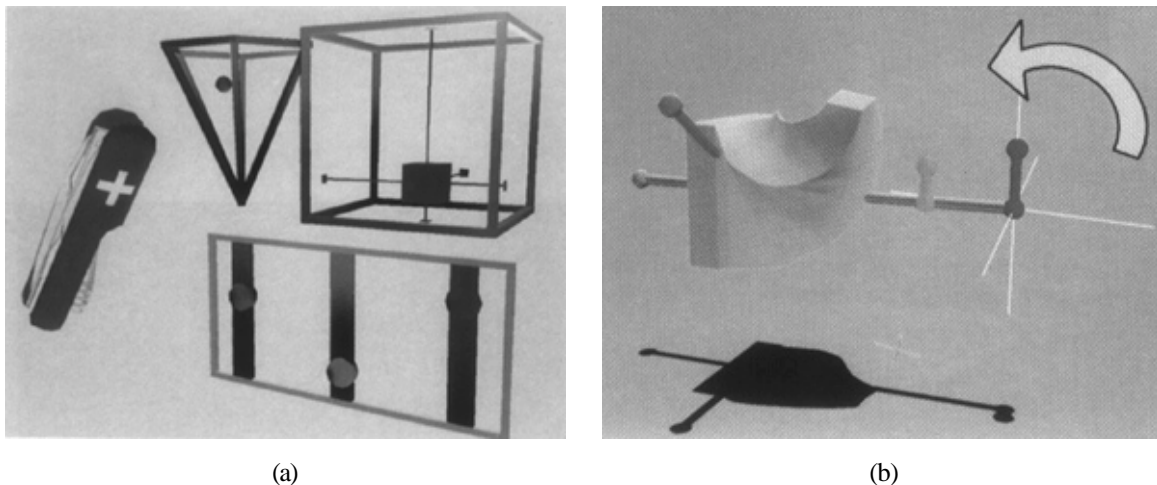
Figure 2.4.2.1. Manipulation of object with the help of 3D widgets:
(a) color-picker widgets, (b) rack widget (from [Broo92a]).

Information accessing

Nowadays, huge amounts of information are stored in computer memory and flow through computer networks. These streams of data will be growing rapidly in the near future (data-highways). The real problem will be rapid retrieval and comprehensive access to the relevant information for a particular user. Standard computer interfaces are not capable to guarantee this any more. Virtual reality with its broader input and output channels, autonomous guiding

agents [Ehma93] and space metaphors [Benf95] offers the enhancement of human perception and makes information searching and understanding faster [Caud95, Mapl95].

To make the interaction and communication with virtual worlds successful we cannot think just about one of previously listed interaction techniques. For each application area, other subset of them will be needed to guarantee the optimal performance. Ideally, not only software but also hardware should be transparent to the user and should provide maximum freedom and naturalness. To achieve this, however, both refinement of hardware devices and software paradigms for interaction are necessary.

2.4.3.   Rendering of virtual worlds

The previous section described, the data structures and rendering approaches concerned with them. This chapter will address other aspects of visualization of virtual worlds like camera transformations, image generation and stereoscopy.

Visual display transformations

The visual display transformation for VR is much more complex than in standard computer graphics. On one hand, there is a hierarchical scene database containing a number of objects (like in standard computer graphics) and on the other hand is the user controlling the virtual camera by moving his/her head, flying through the world, or manipulating it (e.g., scaling). To provide a proper view of the scene, all these components are to be taken into consideration. The determination of viewing parameters involves the calculation of a series of transformations between coordinate systems (CS) that depend on hardware setup, user's head position and state of input devices [Mine95a, Robi95] (see fig. 2.4.3.1). This section describes how to calculate display transformations for rendering of monoscopic images; for details concerning the generation of stereoscopic images refer to the next section.
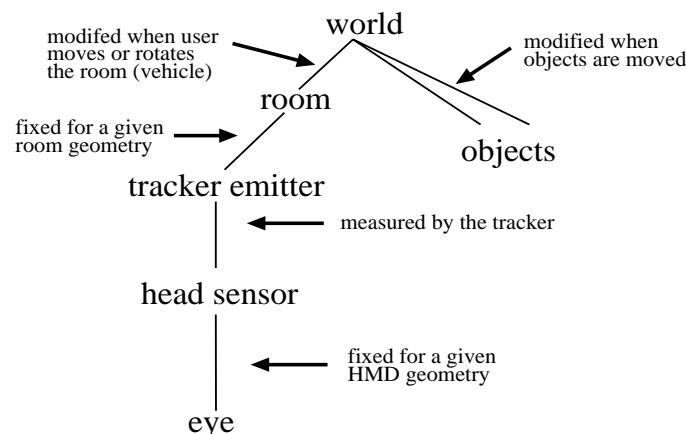

Figure 2.4.3.1. Coordinate system transformations for virtual reality (adapted from [Mine95a]).

To render the images we must know where the camera in the virtual world is. Therefore following transformations must be calculated:

- **Eye-In-Sensor** – defines the position of the eye (virtual camera) in the tracker's sensor CS. These transformations (for left and right eye) are fixed for a given HMD geometry (different HMDs can have tracker's sensors mounted differently).

- **Sensor-In-Emitter** – defines position and orientation of the sensor in the tracker's emitter CS. This transformation changes dynamically as the user moves or rotates his/her head and is measured by the tracking device.

- **Emitter-In-Room** – defines position and orientation of the tracking system in the physical room it is placed in. This transformation is fixed for the given physical tracking system setup in room.

- **Room-In-World** – defines position and orientation of the room (or user controlled vehicle) in the world CS. This transformation changes dynamically according to the user's actions like flying, tilting or world scaling.

To resolve the final viewing transformation (from the object CS into the screen CS) we must additionally take into account the viewing perspective projection and Object-In-World transformations like in standard computer graphics [Fole90].

Stereoscopy

Our two eyes allow us to see three-dimensionally. Stereo vision relies on additional depth-cues like eye convergence and stereopsis based on retinal disparity [McKe92b, Hodg93] (see fig. 2.4.3.2) and therefore may greatly increase the feeling of immersion.
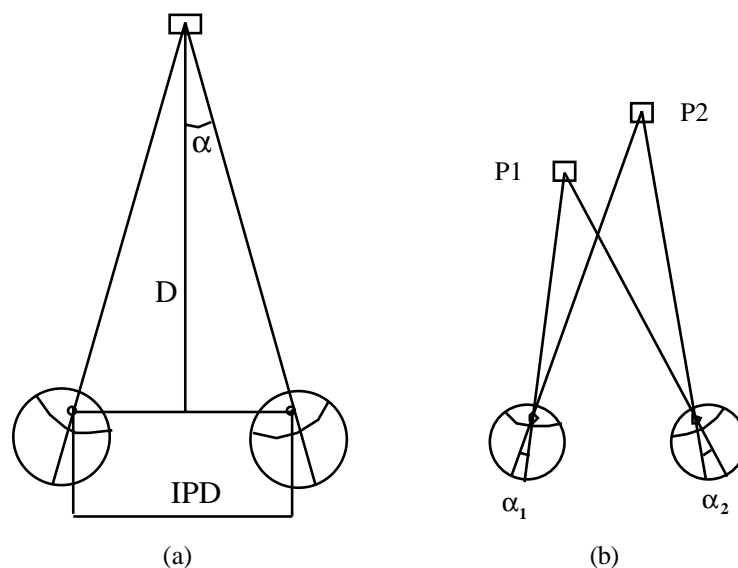

Figure 2.4.3.2. Stereoscopic depth-cues: (a) eye convergence, (b) retinal disparity (from [Sche94]).

For stereo perception in computer graphics we must generate proper pairs of images (stereo pairs). There are two kinds of VR systems that require different visual display transformations in order to produce the proper stereoscopic images – Fish Tank VR and immersive systems (i.e. systems that use HMDs):

- **Fish Tank VR** – these systems use a standard desktop monitor to present the images. The user is equipped with a head tracker and appropriate 3D glasses (see section 2.5.1). Stereoscopic images are mainly created with the help of the *off-axis projection* [Hogd92]. This method uses two asymmetrical projections that are not centered on the main projection axis (see fig. 2.4.3.3a). Alternatively a *crossed-axis projection* [Hodg92] can be applied. In this approach the angle of convergence at the viewed point (see fig. 2.4.3.4a) is used as the rotational angle for the scene (see fig. 2.4.3.4b). The rotation is easy to implement, but it can produce *divergent* and *vertical* parallaxes (parallax is the distance of homologous points on the screen). A divergent parallax can occur when there are points that are far away from the center of rotation. Their parallax will get bigger the further they are away, so the parallax is unbounded. Vertical parallax occurs when an object is rotated under perspective projection [Sche94]. These artifacts can greatly affect image quality.

- **immersive systems** – these systems use a HMD to present images to the user. They use the *on-axis projection* [Hodg92]. For a generation of stereo images this method uses parallel viewing rays for each of the eyes and the perspective projection (see fig. 2.4.3.3b).
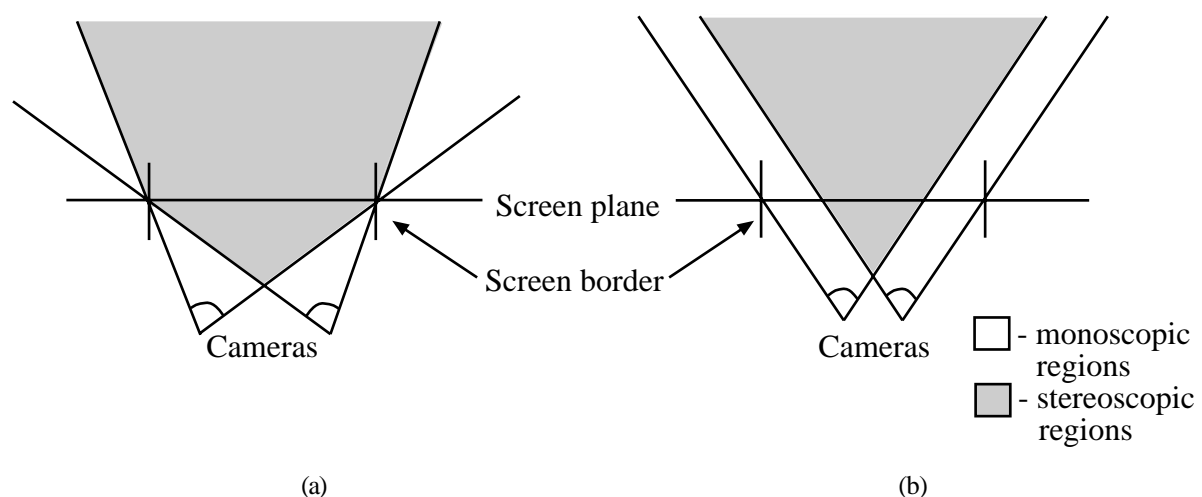

(a)   (b)

Figure 2.4.3.3. Two centers of projection transformations:

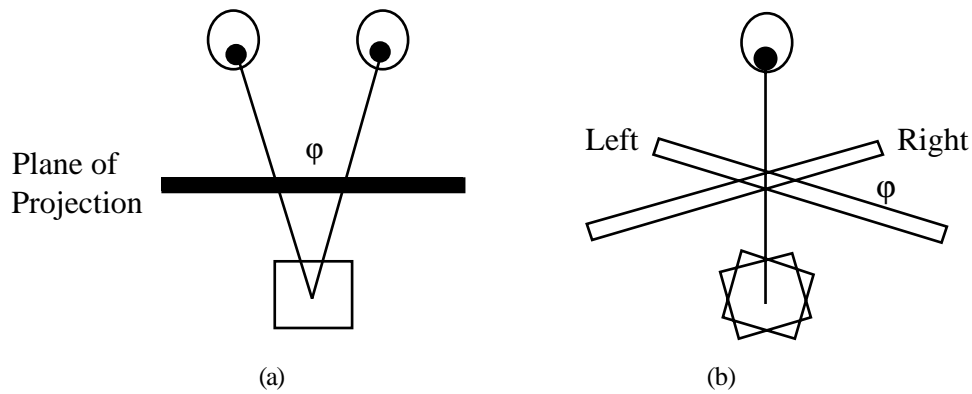(a) off-axis projection, (b) on-axis projection (from [Sche94]).

Figure 2.4.3.4. Crossed-axes projection: (a) eye convergence, (b) scene rotation (from [Sche94]).

Both of the two centers of projection methods (off-axis and on-axis) generate a proper perspective but have the disadvantage that they create regions where only monoscopic information is present (regions that are seen by only one of the eyes).

For the design of a stereoscopic system special considerations are to be taken into account, because even very little distortion (caused by optics geometry or incorrect transformations) may hinder the fusing of proper three-dimensional images [Robi92a, Jian93].

Image generation

Image generation is crucial in every VR system. Some aspects of it (like constant frame-rate rendering and CS transformations) were already addressed in previous sections, but there is one more important issue to mention: *speed*. To sustain an immersion feeling a high frame rate is required, but visual scenes are getting larger and more detailed (the number of polygons in the viewing frustum is growing). These two needs are addressed by high performance hardware image generators (IG). Several vendors like SGI, Intergraph, Evans&Sutherland, Division or SUN offer a variety of graphics boards that have different speeds, capabilities and prices. The following properties must be considered [Last95]:

- **performance** – specifies how many Z-buffered polygons (generally triangles) per second can be rendered. To achieve the peak performance triangle strips (meshes) are used.
- **shading** – which shading algorithms are implemented in hardware: flat, Gouraud or Phong.
- **lighting capability** – possibility of hardware assisted color calculation (based on e.g., defined light sources and material definition). This allows the use of models that do not have precalculated vertex colors.
- **texturing capability** – possibility of texture mapping. This approach allows the dramatic reduction of the scene geometry: instead of many small polygons, large textured polygons are used. This also increases the quality of rendered images.

The best graphic boards available on the market (e.g., RealityEngine[2] from SGI) provide up to 1.6 millions of 50 pixel, unlighted, flat-shaded and Z-buffered triangles (in mesh) per second. Generally all graphic accelerators support lighting calculations and Gouraud-shading; very few can perform Phong-shading. Use of these features, however, causes a performance penalty. The use of textures in image generation can bring advantages: a smaller number of polygons is required to achieve the expected image quality. The most prominent graphics board to date in this field, RealityEngine[2] can render nearly one million of 50 pixel textured polygons per second.

The use of hardware IG brings many performance advantages, but still cannot produce images instantaneously. Therefore, alternative rendering techniques, hardware architectures and configurations are developed constantly. Many of them base on the assumption that the biggest error by the dynamic image viewing, is caused by head rotations. These approaches try to resolve the dependency between orientation data coming from the tracker and the rendering process. The first successfully performed attempt was the CAVE environment [Cruz92, Cruz93b] (see also section 2.5.1) followed by the Virtual Portal [Deer93a]. In both of these systems the user, instead of wearing a HMD, steps into a room whose walls are the projection screens. This approach reduces the latency-based rotational error of head movement to zero, because all the surrounding images are rendered based on the user's position only. The statistical data (only 2 from 9,000 people visiting the CAVE, experienced enough nausea to complain about it) confirms this fully [Cruz93b]. A special hardware architecture – the address recalculation pipeline [Rega94] – is built on the same principle, but allows the user to wear a HMD. Six images are rendered in parallel on six walls of a fictive cube (six separate frame buffers). This approach allows – similarly how it was done in CAVE – to detach the user's orientation from the rendering process. As soon as the rendering is completed, the user's orientation is measured and the appropriate pixels are copied into the final frame buffer.

An obvious extension of the CAVE rendering paradigm are cylindrical [Chen95] and domed displays [Lant95]. In case of cylindrical displays (as used by QuickTime VR for Macintosh) successive frames are rendered from a panoramic 360° high resolution photograph. This approach can eliminate the distortions caused by the rendering on flat screens and requires the pixel-copy operation only. Consequently this leads to a great reduction of the rendering cost: a desktop computer without any hardware accelerated graphics can perform a real-time walkthrough! A spherical projection (which is the ultimate one because of the human eye structure) can additionally enhance the movement freedom – in this case the user can not only rotate his/her head left and right, he/she can also freely look up and down.

The combination of pixel-based techniques with high power image generators can bring many advantages. The rendering of successive encapsulating surfaces can be performed

detached from the user's orientation, and the cost of the final image presentation is constant, because it does not depend on the scene's complexity. This leads to a radical reduction of motion-induced viewing errors.

2.5.   VR output devices

2.5.1.   Visual displays

Most research focused on presentation of visual information to the user. Beside fast view updates, image quality plays an important role for generation of immersion feeling. Section 2.2.1 (visual perception characterization) gave an overview of the most important properties of the human visual system that must be taken into consideration for constructing visual displays. The ideal display should have high resolution, high update-rate, wide field of view, high brightness and contrast. On the other hand wearability cannot be forgotten: ease of use, small weight etc. [McKen92b, Brys93e, Jian93, Holl95, Last95]. Unfortunately, manufacturing a HMD that fulfills all these needs is beyond today's technology possibilities.

Technology

Two display technologies are currently available on the market:

- **CRT** – cathode ray tube displays are based on conventional television technology. They offer relatively good image quality: high resolution (up to 1600x1280), sharp view and big contrast. Their disadvantages are high weight and high power consumption. They also generate high-frequency, strong magnetic fields that may be hazardous to the user's eyes [Holl95] and may have negative influence on the quality of measurements of magnetic trackers.

- **LCD** – liquid crystal diode displays are a relatively new technology that is alternative to standard CRT displays. LCD displays are flat, lightweight, have low power consumption and lower emissions than CRTs. The biggest disadvantage is poor image quality: low contrast, brightness and resolution (typically up to 720x480) [Holl95].

The small size of displays used in HMDs brings with it small FOV. To enhance the viewing range special optics may be used such as LEEP or Fresnel lenses [Robi92a, Brys93e]. Both of these approaches require a predistortion of the image that will be viewed through the special optics (see fig. 2.5.1.1). Wide field optics is used for example by VPL Research for the construction of their HMDs.

(a)   (b)
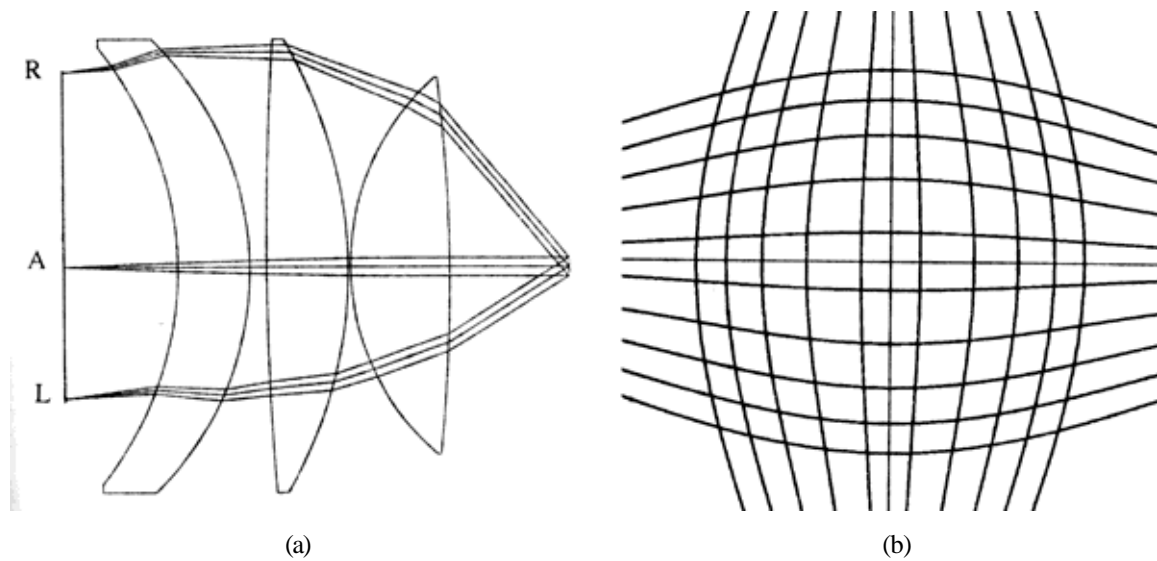
Figure 2.5.1.1. LEEP optics: (a) tracing of rays through the LEEP optics,
(b) predistortion grid for the LEEP optics (from [Robi92a]).

Beyond CRTs and LCDs, a virtual retinal display (VRD) was proposed [Koll93, Tidw95]. A prototype of a VRD developed at the HITLab uses a modulated laser light that projects the image directly onto the user's retina. Although application of this system in practice is questionable nowadays, it offers great potential quality improvement – the goal of the project is to achieve a resolution of 4000x3000 and a FOV bigger than 100˚.

VR visual output devices

Different type of VR systems – from desktop to full immersion – use different output visual displays. They can vary from a standard computer monitor to a sophisticated HMDs. The following section will present an overview of most often used displays in VR.

3D glasses

The simplest VR systems use only a monitor to present the scene to the user. However, the "window onto a world" paradigm can be enhanced by adding a stereo view by use of LCD shutter glasses [Deer92]. LCD shutter glasses support a three-dimensional view using sequential stereo: with high frequency they close and open eye views in turn, when the proper images are presented on the monitor (see fig. 2.5.1.2). An alternative solution uses a projection screen instead of a CRT monitor. In this case polarization of light is possible and cheap polarization glasses can be used to extract proper images for each of the eyes. A head movement tracking can be added to support the user with motion parallax depth cue and increase the realism of the presented images.

Figure 2.5.1.2. Crystal Eyes LCD shutter glasses.

Surround displays

An alternative to standard desktop monitors are large projection screens. They offer not only better image quality but also a wider field of view, which makes them very attractive for VR applications. The total immersion demand may be fulfilled by a CAVE-like displays (see fig. 2.5.1.3), where the user is surrounded by multiple flat screens [Cruz92, Cruz93b, Deer93a] or one domed screen [Lant95]. Ideally it would support full 360° field of view (see section 2.4.3 on image generation as well). The disadvantage of such projection systems is that they are big, expensive, fragile and require precise hardware setup.
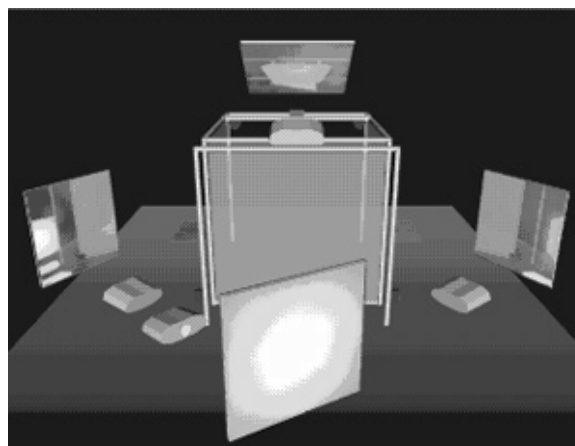

Figure 2.5.1.3. Surround display diagram: CAVE.

Binocular Omni Oriented Monitors (BOOM)

Developed and commercialized by Fake Space Labs BOOMs are complex devices supporting both mechanical tracking (see section 2.3.1) and stereoscopic displaying technology. Two visual displays (for stereo view) are placed in a box mounted to a mechanical arm (see fig. 2.3.1.5). The box can be grabbed by the user and the monitors can be watched through two holes. As the mechanical construction supports usually counter-balance, the displays used in the BOOMs need to be neither small nor lightweight. Therefore CRT technology can be used for better resolution and image quality.

Head Mounted (Coupled) Displays (HMD)

HMDs are headsets incorporating two small CRT or LCD monitors placed in front of the user's eyes. The images are presented to the user based on his/her current position and orientation measured by a tracker (see section 2.3.1). Since the HMD is mounted to the user's head it must fulfill strict ergonomic requirements: it should be relatively light, comfortable and easy to put on and off. As any visual display it should also have possibly the best quality. These demands force engineers to make hard trade-offs. Consequently, the prices and quality of HMDs vary dramatically: from about 800 dollars for a low-cost, low-quality device to about one million (!) dollars for hi-tech military HMDs [Holl95].

    HMDs can be divided in two principle groups: *opaque* and *see-through*. Opaque HMDs totally replace the user's view with images of the virtual world and can be used in applications, that create their own world like architectural walkthroughs, scientific visualization, games etc. See-through HMDs superimpose computer generated images on real objects, augmenting the real world with additional information (see also section 1.3.2). Most of the HMDs currently available on the market support stereo viewing and can be driven either with PAL or NTSC monitor signals [Vinc95].
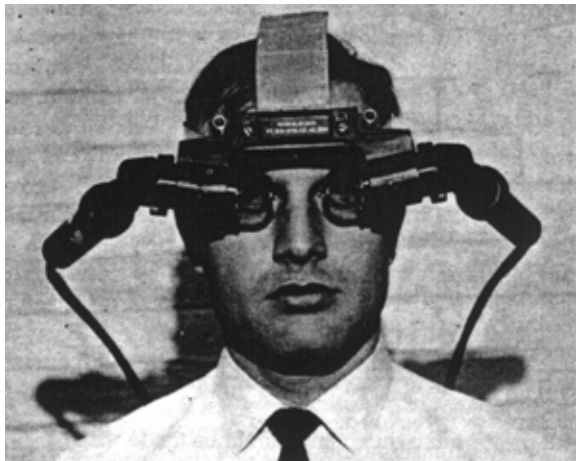
(a)

(b)

(c)

(d)

Figure 2.5.1.3. Different Head Mounted Displays: (a) Ivan Sutherland's HMD dated from 1968,

(b) low cost CyberMaxx HMD, (c) advanced military Sim Eye HMD,

(d) low cost see through HMD "i-glasses!" from Virtual I/O.

Name	Type	Technology	Resolution (H x V)	FOV (H x V)	Est. price (USD)
Sim Eye	see-through	CRT	1280x1024	60˚x40˚	200,000
CyberMaxx	opaque	LCD	180K pixels	60˚x53˚	800
EyeGen3	opaque	CRT	123,250 pixels	35˚x30˚	10,000
i-glasses!	opaque or see-through	LCD	180K pixels	30˚ horizontal	800

Table 2.5.1.1. Technical data of example HMDs.

2.5.2. Haptic displays

Haptic sensations perceived by humans can be divided into two main groups:

- **kinesthetic (force) feedback** – forces sensed by the muscles, joints and tendons.
- **tactile feedback** – includes feedback through the skin, like sense of touch, temperature, texture or pressure on the skin surface.

These perception issues are extremely important when performing some precise manipulation tasks. Manipulating every object in real world always causes a collision between the hand and this object, which is perceived as haptic feedback. Therefore the many of dexterous manipulators and some data gloves (see section 2.3.3) are equipped with devices simulating these sensations [Giga93c, Vinc95]. A remote interaction with fragile objects (e.g., human eye surgery or laboratory tasks) could not be completed accurately without proper haptic cues.

Force feedback

Object placement and manipulation requires a proper force, which is a quite natural phenomenon for humans. To increase the naturalness of interaction in VE some devices are equipped with force feedback. This includes a variety of manipulators from simple gloves [Burd92] to sophisticated and mechanically complex exoskeletal hand masters (see fig. 2.5.2.1).

Beside these hand mounted manipulators that are supposed to simulate the real interaction with objects, several studies have proven that presence of force-feedback increases efficiency of various placing and manipulation tasks. Therefore many devices were developed: from the simplest ones like joysticks or desktop mice [Akam94] with kinesthetic feedback, through force simulation with help of tense strings [Ishi94a, Ishi94b] to the UNC GROPE project [Broo90]. All of them confirmed qualitative improvements of interaction – it has been found out that haptic display together with visual one, can enhance the perception and understanding of natural phenomena like for example scalar or vector fields. The latest prototype of GROPE consists of a ceiling-mounted arm (see fig. 2.5.2.2) coupled with a computer and was used by the chemists for a drug-enzyme docking procedure. The application in other areas like molecules or proteins properties investigation seems to bring big advantages.
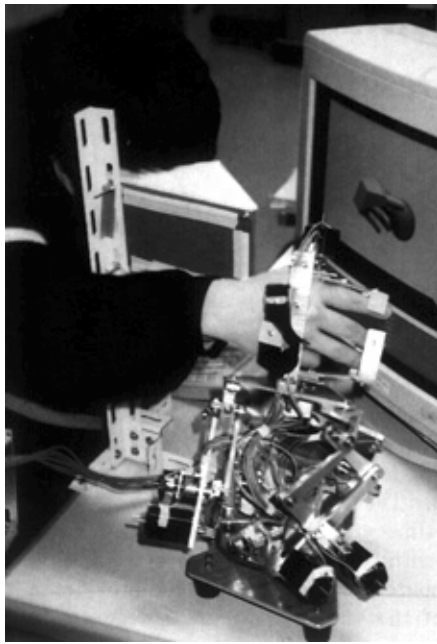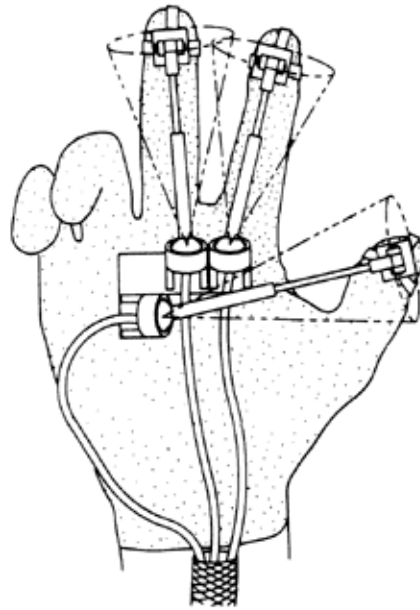
(a)   (b)

Figure 2.5.2.1. Force feedback hand masters: (a) Master Manipulator (from [Iwat90]),

(b) force feedback structure for the data glove (from [Burd92]).
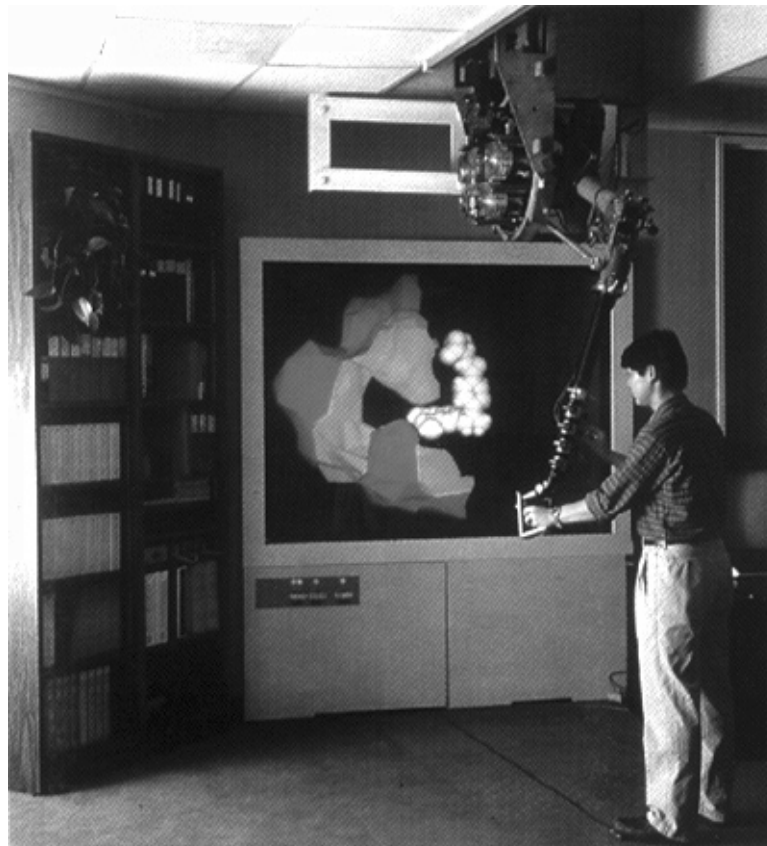
Figure 2.5.2.2. GROPE-III force feedback display (from [Broo90]).

Tactile feedback

Tactile feedback is much more subtle than force feedback and therefore more difficult to generate artificially. The simulation may be achieved with the help of vibrating nodules, inflatable bubbles or electrorheological fluids (fluids whose viscosity increases with an applied electric field) placed under the surface of a glove [Monk92, Giga93c, Holl95] (see fig. 2.5.2.3). All these currently available technologies are unable to provide the whole bandwidth of sensory data we obtain through our skin. They generate the indication of touch with some surface but do not allow the user to recognize its structure.

Figure 2.5.2.3. CyberGlove equipped with tactile feedback units.

2.5.3. Audio displays

Sound can powerfully enhance the human perception ability. As an addition to the visual information, auditory information can offer several benefits like [Wenz92, Barg93, Asth95, Hahn95]:

- additional channel of data passing
- perception ability of information that is outside of visual display
- alert or focus signals that attract the user or warn him/her
- spatial orientation cues
- possibility of parallel perception of many information streams

In the simplest case, sound can indicate completion of some tasks or signal that some conditions have been met (like collision with objects, placing of bodies etc.) without cluttering the screen. This technique has been used for a long time in desktop systems and includes click-keyboards or desktop sounds (including speech audio too) confirming certain actions or system events. For these purposes a monaural sound is sufficient. In VR, however, more convincing three-dimensional auditory displays can be used to simulate distance, direction, material and spatial information about the environment. A successful area of application is architectural visualization. Sound cues lead to better spatial impression and allow visual and acoustic evaluation of buildings models, which is a big improvement for walkthrough applications.

To generate these spatial cues convincingly basic knowledge of the human sound localization system is required. The *duplex theory* [Wenz92] accents the two primary hints that play a leading role in this process: *interaural time difference* (ITD) and *interaural intensity difference* (IID) (see fig. 2.5.3.1).
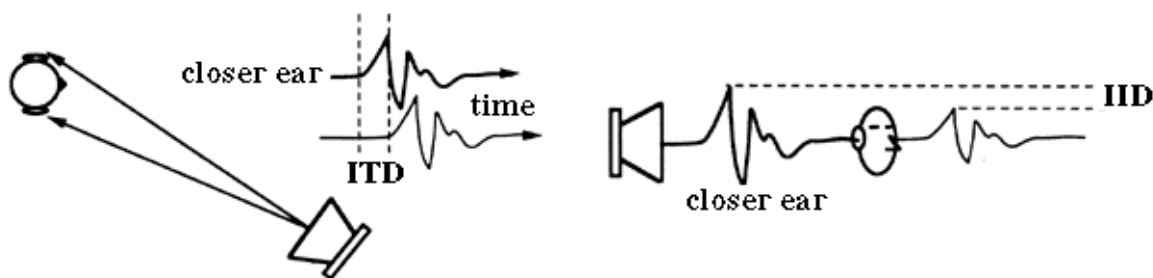
Figure 2.5.3.1. "Duplex theory" spatial cues: (a) interaural time difference, (b) interaural intensity difference (from [Wenz92]).

Beside these two basic cues, other aspects should also be taken into account. Spatial information reaching our ears strongly depends on the distance from the source, environment geometry and material properties of objects in vicinity, which influences the creation of echoes. At least the listener's pinnae (outer ear) has influence on spectral sound wave shaping by reflecting and refracting it slightly. All these subtle effects altering the sound received by the ear create the effect of spatial sound perception.

To synthesize artificially the sound that matches human perceptual abilities is a complex and computationally expensive task. Moreover, the proper synchronization of sound and visual events is extremely important in order not to disorient the user by contradictory cues. Three basic steps are required for successful simulation of virtual acoustic environments [Asth95]:

- **sound generation** – every action in real world generates some sound (steps, object collisions etc.). For acoustic simulation sound can be either generated (synthesized) or sampled and played back.

- **spatial propagation** – this is the most expensive part of the whole simulation: it involves calculation of spatial propagation of sound waves through the environment. Ideally all the reflections (echoes) from different objects and walls should be considered according to the material properties and surface shapes of these objects.

- **mapping of parameters** – finally the calculated parameters should be mapped onto proper sounds that will be delivered to the listener through headphones or speakers. To do this, all rendered chunks (impulses) should be convoluted together, by use of special filters, to produce one sound. The directional effect can be achieved by use of ITD and IID cues and calculation of Head-Related Transfer-Functions (HRTF) [Wenz92].

3. The future of VR

The future of every new technology, including virtual reality, must be considered in two different aspects: *technological* and *social*. Technological aspects include new research directions and potential use of them for scientific aims. Social aspects include the influence of new inventions on people: individuals and society as a whole.

3.1. Research directions in VR

The idea of the ultimate virtual environment as stated by Sutherland [Suth65] means that VR should be indistinguishable from "real" reality (RR). Most of today's VR applications do not conform to reality and have poor quality, but are still very useful and persuasive. Without doubt VR has a big potential, but must be improved a lot to allow more comfortable and intuitive interaction with virtual worlds. It does not have to simulate reality in every inch of existence: for training, the simulation should closely match real operating conditions, while e.g., in the UNC's nanomanipulator application we do not even have any reference to reality (since humans cannot experience the interaction with molecules in real life).

Independently from the application and its purpose, human factors *must* be considered (see section 2.2) or the system will fail to be sufficiently comfortable and intuitive. There is need for mechanisms allowing people to easily adapt themselves and their behavior from VR to reality and vice versa. To address these requirements better than current systems do, a lot of research must be carried out and new technologies must be developed [Fuch92, Broo94]. Therefore Andries van Dam called VR a "forcing function" [VanD93].

3.1.1. Ergonomics of visual displays

Up to now, the major interest was paid to visual feedback and visual display technologies. Nevertheless the quality of nowadays shipped HMDs is far from ideal: resolution is significantly below eye's resolving capability, luminance and color ranges do not cover the whole eye's perception range (brightness range and gamut respectively), and finally the field of

view is relatively narrow. All these disadvantages make virtual worlds appear "artificial" and unreal, which severely contributes to the simulator sickness.

Despite continuous improvement of operational parameters, LCD- and CRT-based HMDs (currently at 1280x1024 resolution on 1.2"x1" area [Burd94]) will not offer the ultimate quality. To overcome these miniaturization problems a competitive solution was presented recently by HITLab – a virtual retinal display [Koll93, Tidw95]. It uses a laser beam that projects images directly on the user's retina. Nowadays this technology offers approximately the quality of an average LCD screen. Yet, it is very promising: theoretical limits of such displays are essentially equal to the limits of the human eye.

An alternative approach for presenting images to VR user(s) are large projection screens. Images can be seen with bare eyes, have better brightness and resolution than typical HMDs. Stereo viewing is possible with light and comfortable LCD shutter- or polarization-glasses. For the full immersion (360˚ look around) CAVE-type displays or recently introduced domed projection screens can be used [Lant95]. Toshiba Corporation has lately developed a "volume-scanning" display consisting of many slices of semi-transparent LCD screens. This new technology allows three-dimensional viewing of stereoscopic images without any additional equipment [Kame92, Kame93].

3.1.2. Tracking technologies

Today's tracking technologies have many limitations. First and foremost: in many cases the tracked volume is very restricted. In practice the user is bound very closely to some point in space (i.e. tracker reference point) and cannot walk around freely. Moreover, the quality of tracking is often not sufficient – most of currently used technologies are very sensitive to environmental conditions (the quality of measurement decreases dramatically with the distance) and introduce considerable latency.

An ideal tracker should be small and lightweight so that it can be comfortably worn by the user. The working volume for the *inside tracking* should be big enough to allow free walking for example in a big room (ten by ten meters?). And at least, the tracker should be immune to any kind of interferences that would guarantee the equally high measurement precision in the whole volume.

A partial solution for the *inside tracking* was developed at the UNC – the "optical ceiling" that allows tracking of the user inside an area of about three by four meters [Ward92]. This approach gives the user unbound movement freedom and equal tracking precision in the whole working volume. The inside-out tracking paradigm used in this system offers good quality of orientation measurement but position measurements still lack the requested precision. The whole installation is relatively expensive (needs ceiling LED panels and proper controlling of

them) and requires heavy optical equipment (cameras) to be attached to the HMD. Nevertheless it is currently the best alternative for the ultimate inside tracking.

The idea of *outside tracking* is very promising – it may open new possible applications of VR, like navigation systems or place-sensitive information services. The currently existing Global Positioning System (GPS) does not offer quality of position measurement that is sufficient for virtual reality yet, but further development in this area may bring the required improvements. Such a high precision GPS in combination with source-independent orientation tracking devices (as used by the i-glasses! for example) may become then a solution for medium quality but cheap and wide-spread global VR or AR systems.

3.1.3.   Computing power and rendering architectures

Behind all virtual worlds a high computing power is hidden. It is the "engine" for the generation of all kinds of feedback presented to the user. Though the most powerful computers are used in VR, there is a continuing hunger for more MIPS and megabytes. More detailed and impressive scenes require more storage capacity, more CPU performance and graphical power. Therefore new processors and graphics boards are being developed in order to fulfill these needs. In practice, however, standard UNIX workstations are utilized for VR applications that do not guarantee real-time operation (UNIX is not a real time system!) and VR specific requirements like constant frame-rate rendering (see section 2.4.1) or dynamic image registration are compromised.

To overcome limitations of standard rendering architectures some novel VR systems correct already rendered image before displaying it. Just to mention approaches that can be implemented on conventional workstations like image deflection [So92, Mazu95a], Z-buffer warping, image generation from the panoramic (360°) photograph [Chen95] or dynamically generated impostors [Maci95, Scha95b, Scha96b]. Other more complicated methods require custom hardware architectures like address recalculation pipeline [Rega94], frameless rendering [Bish94] or "just in time pixels" [Olan95]. The common aim of these techniques is to minimize the dynamic viewing error (when the user moves through the scene). Combined with prediction methods [Liang91, Azum94, Mazu95a], it is possible to achieve an essential improvement of registration in virtual reality and augmented reality systems.

Finally, widely acknowledged and cross-platform standards – in particular for device drivers and APIs for these architectures are needed. Only this can assure rapid and (relatively) easy development of new systems without a need for "hand-crafted" programming.

3.1.4.   User interfaces

"VR means that no interface is needed": every kind of human-computer-human interaction should be so natural and intuitive that neither learning nor adaptation should be necessary. Though, we are far from this: today's interfaces are clumsy, often require heavy hardware devices, complicated calibration steps and non-intuitive interaction paradigms. Hence they are not easy to operate by the unskilled user.

Future interaction with virtual worlds should involve better input and output devices. Every input device should be at the same time an output device that supports appropriate haptic feedback. This is essential, because every action performed in the real world on some object causes a reaction of this object. These cues allow humans to perform manipulation tasks without seeing what happens – our sense of touch informs us about it! Other senses must be included into the interaction process like audio output and voice recognition for verbal communication with computer and finally: taste and smell. Combination of all these sensations would widen information passing channels between computer and human and make virtual reality *really realistic*.

Gloves with feedback, dexterous and exoskeletal manipulators (for the hand and even whole arm) are the first attempt to improve high quality haptic interfaces [Rohl93b, Stur94]. An extension of them might become a force feedback suit [Burd94] delivering haptic sensations to the whole body. However, existing prototype devices are very complicated mechanical constructions, heavy and uncomfortable in use.

Computer generated voice feedback (speech-audio) already does not seem to be a problem. To fulfill the need of human-computer communication (e.g., with computer generated autonomous actors or agents), speech recognition is also necessary. There is a couple of commercial systems [Holl95] claiming good accuracy of recognition, with prices ranging from 150 to 30,000 US dollars. Very few of them, however, support big dictionaries and continuous speech processing (whole sentences vs. single words). While it is easy to recognize and analyze simple orders, the real problem is learning the computer to understand what the user intents (in fact it is the Artificial Intelligence problem). Moreover, the high computing power for the recognition and long training of the user are required.

3.1.5.   "Seamless" virtual environments

Majority of VR research directions concentrated up to now, generally on the technical aspects. The improvement of the performance, quality and responsiveness of virtual worlds was the main problem. However, most of currently existing systems are in fact only test-beds that cannot be used in any practical application. To construct "seamless" virtual environments proper high-level software must be developed as the basis for "real" applications [Zyda93d]. To

achieve this aim, following most important issues must be taken into consideration like *modeling interactive worlds*, *distributed multi-user architectures*, *effective user interaction* etc. [Fuch92, Zyda93d, Broo94].

Modeling is a crucial problem of virtual environments. Additionally the user must be able to interact with the created model as with the real world. Therefore automatic world building tools that allow easy, intuitive and inside-the-environment modeling are needed. Moreover, the modeled objects should have natural behavior assigned to them (in some cases also autonomous behavior), and very often they should obey the rules of physics. Such modeling tools have a big potential to fuel the development of a broad variety of new VR applications.

Another important aspect are multi-user systems: in real world people share the same space at the same time with other humans. To meet the same requirements in virtual worlds, the model must be shared among multiple users (let each of them manipulate the model) and must be properly updated in order to remain consistent. The today's networked information spaces are still largely research prototypes. They are usually limited to a small number of users and run on local networks for performance reasons. The example of large scale system is NPSNET [Mace94] that works with a large number of concurrent users, but its underlying networking protocol severely limits the variety of possible actions. Therefore further development in this direction is necessary in order to support cooperative work, multi-user training and collaboration with the help of VR.

3.1.6. Biomedical research

Sophisticated input and output devices are some of the most expensive parts of VR systems. The development in the area of microelectronics gives a hope that new, high power "silicon architectures" will be elaborated relatively fast. On the other hand, current "standard" output and input devices are far below the satisfying quality. The improvement of them (better resolution, precision etc.) is extremely expensive mainly because it is bound by technological frontiers.

To overcome these problems, biomedical signal processing could be used both for input and output. Based on biosignals measured by electrodes, muscle activity could be detected [Lust93]. By processing these signals, the positions of body parts could be tracked. Moreover, this approach can be used for improvement of existing motion prediction techniques (e.g., head movement). Knowing neural signal patterns that force muscle actions and knowing the head "transfer function" (i.e. how the head reacts on muscle input), one could more precisely predict the future position and orientation of the head.

The output of computers can be directly connected to the human nerves: instead of building high (but still too low for the human eye) resolution displays, images could be fed directly into the eye nerves, instead of providing force and tactile feedback, appropriate nerves in different

parts of the body can be stimulated and so on. Ultimately one can imagine the direct stimulation of brain cells in order to artificially generate sensations perceived by human senses. One could just "plug" himself/herself into the computer as envisioned in William Gibson's science-fiction novels [Gibs83]. The only question is: Is this what we really want?

3.2.   Social aspects

Virtual reality is in its experimental stage today, but without doubt it has a great potential to alter our life. People expect very much from this technology – much more than it can offer yet. But there is the other – "dark side": every new technology and every new invention brings a fear and feeling of uncertainty with it (e.g., nuclear power). It can be used for good aim, but it can be misused too. The more potential it has, the bigger the danger can be.

3.2.1.   What are the expectations?

VR has found already an enormous number of applications in different areas of science (see section 1.3). It became a perfect tool for architects, designers, physicists, chemists, doctors, surgeons etc. All these disciplines, however, are closed for average people and therefore virtual reality is becoming some kind of myth – something extremely wonderful (a Promised Land?) and at the same time something inaccessible.

Due to the high cost and fragility of equipment, up to the end of 1980 VR was hidden behind laboratory walls. But in the beginning of the current decade a great interest of media dragged it to the wide publicity. Moreover, the development of cheap and powerful hardware allowed the spread of many installations opened to the public. The first were arcade games [Atla95] – computer games extended by an immersion feature using a HMD and a tracking system. The great success of them forced the market appearance of further entertainment systems: multi user car races, dungeon games, flight simulations and others [Atla95].

Beside adventure games in cyberspace there are not many other applications that may have a big influence on people or society yet. Nevertheless, there were already successful attempts of use of the VR systems in medicine (e.g., curing of mental disorders, phobias [Whal93, Vinc95], people with disabilities [Trev94]) and in education [Loef95, Schr95]. In the future, VR technology will have a rapidly growing influence on almost every area of our life:

- **education** – school, a variety of training systems (e.g., driving license courses, sport coaching [Ande93], flight simulation, military or astronauts training etc.), programs explaining laws of nature (e.g., by placing the user between molecules, inside of hurricane or letting him/her explore the galaxy), and even virtual universities without lecture rooms will become usual in near future.

- **information retrieval, processing and searching** – today's society is called an "information society" and the need for new sources of easy accessible data will be constantly growing. VR will offer the easiest access to information through virtual libraries (not only books but films, music, stock-exchange data etc.), office electronic data-files, guided sight-seeing tours (visiting virtual museums, buildings, cities, lands etc.).

- **augmented reality** – with the help of see-through HMDs, additional information can be displayed to the user pointing his/her attention to important objects of the real world, showing the way to the specified aim (e.g., by highlighting the right way through the city) or explaining the next step that must be performed to complete some tasks – from the complex ones like repairing complicated electronic devices or space shuttle elements in open space to easy ones as operating faxes, laser-printers [Brys92c] or changing a car tires etc.

- **new senses** – every information that cannot be acquired by human senses but can be detected by technical sensors may be potentially seen by the user [Robi92b]. For example a doctor may have a direct insight into patient's body [Baju92], an electrician may see wires in walls while fixing house installation or an engineer may see pipelines under the ground when performing digging works etc.

- **passive entertainment** – as new information medium of 21st century, VR will replace majority of passive entertainment activities like reading books, watching movies, TV, listening to the music. In fact all of them will be unified in one big virtually multimedial system.

- **active entertainment** – thanks to VR technology some computer games become more realistic, and in consequence more interesting. It is to expect that other free-time activities like e.g., playing music or sport exercises will be soon altered by VR technology.

- **communication and collaboration** – at work and at home people constantly exchange huge amounts of data by communicating with other humans. Physical meetings that are not always possible due to big distances and other obstacles, are replaced by talking on the phone, or on-screen teleconferencing sessions. One can easily imagine meetings in virtual space, virtual phone talking, virtual mailing and many more (in practice every medium can be replaced by VR). These communication paradigms are not bound by distance constraints and they are a promising alternative to the existing collaboration media.

- **remote operation** – today, a remote operated TV-set is nothing spectacular. VR technology allows to enhance basic idea of teleoperation. It can include really complex tasks that require the dexterity of human hands. Teleoperated robots can in near future replace people at workplaces that might be hazardous to their life of health. This includes

for example maintaining of nuclear power stations, works on height, works with chemicals or viruses etc.

- **interactive design** – in the future every engineer will be able to design and test his/her projects (engines, aerodynamics of bodies or even whole mechanical constructions) with the help of VR. Testing a car, its road behavior, acceleration and other properties is a fascinating and cheap alternative to today's design processes that last very often for years! Eventually, average people will have the possibility to design their houses, hair styles or clothes interactively and see immediately what the result will look like. Every visit at a hair-dresser, tailor, or house designer would start with a VR session.

This list of expectations (or rather: wishes) can be extended infinitely and will never be complete. The fact is that with the development of networks (i.e. data highways), everyone will be able to rent a network line (like telephone or cable TV nowadays) and connect his/her personal workstation (computer equipped with a HMD) to it. Then the use of virtual reality in everyday life will become as common as the use of telephones, hoovers, TV-sets, videos, cars or airplanes today.

3.2.2.   What are the fears?

With the introduction of VR to society there is a need of finding ethical norms for it [Kall93, Whal93]. People also should know about the potential dangers of the new technology: which negative or even destructive influence it can bring along [Sher93, Whit93]. One may not exaggerate because humans have a great ability of adaptation to new conditions: finally they will always find their place in new (even virtual) realities. Nevertheless it is better to prevent than to correct [Kall93].

Virtual reality systems of the future can be divided into four groups according to two criteria: *social* vs. *non-social* and *creative* vs. *non-creative* [Ston93] (see fig. 3.2.2.1).

Non-social virtual realities allow a *single* user to interact with the environment. This can be an interaction either: with a prefabricated (i.e. preprogrammed) environment (they are then called: non-creative systems) or with an environment that can be modified according to the user's needs and wishes (they are then called: creative systems).

Social virtual realities on the other hand allow *multiple* users to interact with each other and with the environment itself. Again, as with non-social systems, the environment can be preprogrammed or it be created and altered by the user or a group of cooperating users.

	non-creative:	creative:
non-social:	**single user & preprogrammed environment**	**single user & modifiable environment**
social:	**multiple users & preprogrammed environment**	**multiple users & modifiable environment**

Figure 3.2.2.1. Four types of VR systems (from [Ston93]).

Different types of VR systems can have different influences on people's mentality. Non-social virtual realities for example may lead to closing of people in their "own worlds". This has already partially happened – some of the most fanatic computer-game players can hardly be forced to come back to reality! And with more convincing and realistic systems, it can only become worse... Non-creative applications (like games) may have an additional negative effect: closing the user in the world that cannot be modified is against human nature and can lead to degradation of our imagination.

Non-social and creative virtual worlds that potentially can be great tool for designers, are at the same time even bigger temptation for complete escape from reality. They offer to the user the possibility of modifying the surrounding according to one's wishes (which is very often not possible in real world). Thanks to it, creating an artificial wonderland of dreams will be as easy as building a house using a Lego-set. With these considerations several existential questions arise: Is our everyday life so bad that so many people escape from it? Will VR make people at least more happy? Which influence will it have on the ability of coexistence with other humans?

This last question, becomes even more important when considering social virtual worlds, allowing people to communicate and collaborate. They can certainly be a great help in work and in everyday life, but are they going to replace physical contacts totally? Even today a lot of people spend hours on the telephone because they are too lazy to pay a visit to their friends. In virtual reality, the user will be able to create an image of himself/herself – often very idealized and far from reality. Hidden behind our masks we will meet only equally "perfect" but cold creatures. How long can one continue living without feelings and how destructive can it be? How easy will it be to come back to reality and make contacts with real people? How easy will it be to switch between real and virtual images, and can it eventually cause a virtual schizophrenia?

Beside the dangers of VR discussed previously, there are other more general hazards. TV has in the 1960s increased the homicide rate in American society [Kall93]. VR can potentially have the same influence on our society a few years from now. People playing brutal games may identify themselves with the virtual heroes and adopt their violent behavior. With the improvement of the simulation and visual quality of virtual worlds the differences between reality and VR will be constantly disappearing and consequently people may become confused what is real and what is virtual. In fact this process has already begun: military simulations are becoming so close to reality that soldiers do not know any more whether they are remotely steering a real "death-machine" or just making a training. This may eventually lead to the lack of responsibility for our actions: one can kill cold-blooded thousands of innocent people not knowing (or rather pretending not to know) if taking part in a simulation or a real mission [Smit94].

All these questions are intentionally left open. The overwhelming evolution of virtual reality technology indicates that there may be an all to real danger for society. VR may become the ultimate drug for the masses. It is our responsibility to choose the right dose.

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